Establishing an IUCRC Center for Microcontamination Control at Northeastern University: a Planning Meeting Proposal

EXECUTIVE SUMMARY

This proposal is for holding a planning meeting for the establishment of an Industry University Cooperative Research Center in Microcontamination Control jointly with the existing University of Arizona and RPI center.

The proposed center's goal is to develop state of the art techniques for micro and nanoscale contaminant control, removal and characterization in manufacturing and fabrication processes. The center will contribute to the competitiveness of the semiconductor, information technology, pharmaceutical, imaging, aerospace and other industries affected by particulate and ionic contamination. One of the main challenges is to increase manufacturing yields through improving dry and wet processes and equipment. Understanding the generation and transport of particulate and ionic contamination during semiconductor processing is of great importance toward the control and removal of these contaminants. The center will especially focus on surface cleaning of patterned, structured and flat substrates. Faculty in the center have identified mechanisms to effectively clean ionic contamination from patterned wafers.

The center will also work toward the development of MEMs based micro-sensors that can be used to detects impurities *insitu* in ultra pure gases used in semiconductor and other processes. A MEMs based MicroGas Analyzer (MGA) is already under development to detect air-borne contaminants such as exhaust effluent monitoring for automobiles, toxic waste incinerators, or chemical analysis on planetary exploration missions. In addition, particle adhesion, which contributes to poor cleaning performance, is encountered in many applications such as post-CMP, wafer handling and many other applications where the adhesion increases with pressure, time, environment or chemical reactions. The adhesion force between particles and substrates is a major issue that will represent one of the research focus areas.

The proposed center will work closely with the industrial members and the existing Microcontamination Control Center at University of Arizona and RPI to develop solutions that will improve the industry's yield and contribute to their competitiveness. The industrial members at all three sites (Arizona, Northeastern and RPI) will share the research results of all the sites. The center will offer member companies the talents of participating faculty and the leverage of pooled research funds.

A. INTRODUCTION

Studies estimate that contamination is responsible for 75% of the yield loss in integrated circuit fabrication[1]. Traditionally, surface cleaning research has been focused on front-end-of-the-line (FEOL) processes where the wafer substrate surface is not patterned. However, contamination also occurs during back-end-of-the-line (BEOL) processes with patterned wafer surfaces. According to the Semiconductor Industry Association (SIA) International Technology Roadmap for Semiconductors (ITRS), the semiconductor industry will face the challenge of contamination removal from 35 nanometer trenches with high aspect ratio (70-100) in the next 14 years[2]. Furthermore, the allowable surface contamination levels will fall dramatically. Critical surface metals are projected to decrease from 9 $x10^9$ to 2.5 $x10^9$ atoms/cm^2 and the organic surface contamination level is expected to decrease from 7.3 $x10^{13}$ to 4.1 $x10^{13}$ atoms/cm^2 in the year 2005. The FEOL critical particle size is expected to decrease from 90 nm to 18 nm in the year 2014. The BEOL critical particle size is expected to decrease from 180 nm to 36 nm in the year 2014.

The need for clean wafers in the fabrication of microelectronic devices has been well recognized since the dawn of solid-state device technology. For instance, a 64-Mb 0.25-μm DRAM process flow has 60 to 70 cleaning steps. In 0.18μm CMOS technology about 80 of 400 process steps will be cleaning. Particles larger than about ¼ of the minimum line-width may cause fatal device defects. As semiconductor device geometry continues to shrink and wafer sizes increase, the limitations of existing cleaning methods on devices yield will become more critical as the size of "killer" particles also shrinks. Physical substrate independent cleaning processes are highly desirable since they do not have to be modified for different substrates (as in a chemical based cleaning process) and do not have a potential for modifying the surface (such as etching, roughening, etc.). Thus innovative cleaning processes are needed to specifically target removal of strongly adherent, nano-scale particles and contaminants.

Cleaning of deep submicron trenches presents a tremendous challenge in semiconductor manufacturing. Preliminary results at the Microcontamination Research Laboratory showed that for both blanket and patterned wafers, pulsating flow cleaning is more effective than steady flow[3,4]. We expect that acoustic streaming utilizing megasonics can be used to effectively clean patterned semiconductor wafers. It was also shown that high frequency acoustic streaming with its thin acoustic boundary layer (in the submicron scale at frequencies higher than 600 kHz) enables the removal of micro and nanoscale particles. Post-CMP (Chemical Mechanical Polishing) cleaning (one of the BEOL steps) is another challenging cleaning application in semiconductor manufacturing. The fundamental phenomenon that needs to be understood is particle adhesion and how it changes during and after the CMP process. Particle removal techniques, in addition to the need to overcome the adhesion force, rely on weakening the adhesion force before or during cleaning for effective removal.

There is a need for reliable and accurate continuous monitoring of impurities in ultra pure gases used in semiconductor processing. The International Semiconductor Technology Roadmap calls for impurities such as H_2O, O_2, H_2, CO_2, CH_4, etc. to be monitored during gas delivery to many processes. A novel micro gas analysis system (MGA) consisting of a microplasma source for gas excitation, a microspectrometer to measure the atomic and molecular emission intensity, and an optical system coupling the light source and detector will be developed. The MGA will provide a compact, low-cost method for detecting gas impurities in semiconductor manufacturing.

A.1 INDUSTRY'S RESEARCH NEEDS

1. Fundamental understanding of surface / interface process science.
2. Understanding of surface cleaning mechanisms.
3. Insitu micro sensors (such as MEMs based micro gas analyzer).
4. Environmentally friendly cleaning and manufacturing processes.
5. Reduction of chemicals and water consumption.
6. Reduction of contamination during wafer handling (e.g. backside wafer contamination).
7. Control of particulate contamination in thin film deposition processes.
8. Predictive physical models.

A.2 RESEARCH FOCUS

1. Fundamentals of surface cleaning and preparation.
2. Physical modeling of particle generation, transport, deposition and removal.
3. Particle adhesion and removal mechanisms.
4. Development and fabrication of in situ micro sensors technology (MEMs based micro gas analyzer
5. Contamination during wafer handling.
6. Reduction of chemical use through dilute chemistries, cryogenic, supercritical fluids, or ozone.
7. Reduction of water use through increased cleaning and rinse efficiency, optimized cleaning and rinse sequences.
8. Contamination in thin film deposition processes (LPCVD, Sputtering, etc.)

A.3 UNIVERSITY CAPABILITY
A.3.1 PARTICIPATING UNVERSITIES, COLLEGES AND FACULTY

Northeastern University Faculty Team

The proposed faculty team will build on the existing strengths in small-scale fluid flow and transport process at the Mechanical Engineering Department at Northeastern and nanoscale characterization and nucleation at the Physics Department. The complementary nature of the research and expertise will build a strong research program in microcontamination.

1. George G. Adams is a professor of Mechanical Engineering. His areas of expertise are the mechanics and tribology of sliding contacts, dynamic response of structures to moving loads, and the mechanics and tribology of microelectromechanical systems (MEMS) and of information storage and processing systems (ISPS). He has published over 50 refereed journal papers and has had many research grants and contracts with government and industry. He is a Fellow of ASME, an Associate Editor of the ASME Journal of Tribology, and an Associate Editor of the Journal of Information Storage and Processing Systems.

2. Ahmed A. Busnaina is the W. L. Smith Chair Professor and Director of the Microcontamination Research Laboratory. His research focuses on defects in semiconductor manufacturing processes such as CVD, PVD, electroplating, etc. He also specializes in wafer cleaning technology, chemical and particulate contamination in LPCVD and sputtering processes, particle adhesion, transport deposition and removal in clean environments. He authored more than 200 papers in journals, proceedings and conferences. He taught more than 30 short courses for semiconductor manufacturing worldwide. He organized 30 symposiums and programs, chaired and organized more than 70 sessions and panels for many professional societies worldwide. He serves on the editorial advisory board of the Semiconductor International Magazine, the Journal of Particulate Science and Technology and the Journal of Environmental Sciences. He is a Fellow of the American Society of Mechanical Engineers, he also was a Fulbright Senior Scholar.

3. John W. Cipolla, Jr. is a professor and the Chairman of the Department of Mechanical, Industrial Manufacturing Engineering. His research has been in the general area of thermofluids engineering with specific emphasis on aerosol mechanics and microscale heat transfer, using background in mathematical modeling of kinetic theory and radiative transport processes. He is a Fellow of ASME.

4. Jeffrey A. Hopwood, is an associate professor of Electrical and Computer Engineering. He is the author of 25 peer-reviewed journal articles and the inventor of 6 US Patents. He is a frequently invited speaker at both international conferences and major university seminars. The relevance of his work is also evidenced by over 800 citations in the scientific literature. Prof. Hopwood's expertise is in plasma processing of materials and state-of-the-art microfabrication methods for microelectronic and micromechanical systems.

5. Nathan Israeloff, is a professor at the Department of Physics. His current research focuses on the nanoscale physics of complex materials, such as polymer and organic glasses and copper oxides. He has considerable expertise in nanoscale electrical transport, dielectric properties, electronic noise, and novel nanolithography techniques.

6. Nicol E. McGruer, is a professor of Electrical and Computer Engineering. His research is in the areas of microelectromechanical systems (MEMS), including work on microrelays, high-temperature optically-interrogated vibration sensors, microspectrometers, and optical communication components, plasma-source ion implantation for semiconductor doping in multiple-process systems, fabrication of 0.1 to 2 micron-scale gated field emission devices, gated field emitter reliability physics, fabrication of 3-D microelectronic circuits, and fabrication of monolithic ferrite devices.

7. Sinan Müftü, is an associate professor at the Department of Mechanical, Industrial and Manufacturing Engineering. His general research area is applied mechanics, numerical modeling of tribology problems; Fluid/structure coupling, and mechanics of moving plates and shells. His research focus is in the area of measurements and theoretical predictions of head/tape spacing over a flat head. Member of ASME, Society of Tribologists and Lubrication Engineers.

University of Arizona and Rensselaer Polytechnic Institute

Participants will be members of the existing IUCRC Microcontamination Control Center faculty and administrators.

A.3.2 FACILITIES AND INFRASTRUCTURE AT NORTHEASTERN

The proposed center has 5500 square feet of cleanroom space that is used for the Microconatmination Research Laboratory and the Microfabrication Laboratory. The facility has all the equipment needed to study surface cleaning, particle adhesion and removal, contamination characterization. The facility is also fully equipped for MEMS fabrication, including extensive lithography, etch, thin film, and plating capabilities with all the supporting infrastructure such as the DI water plant. All the facilities and equipment are described in detail in the facilities section (Appendix) of this proposal.

B. MODEL OF THE ENVISIONED CENTER

B.1 THE CENTER STRUCTURE AND POLICIES

The proposed center at Northeastern University will adopt the industry/university agreement used by the University of Arizona's Center for Microcontamination Control. The organization chart of the center is shown in Fig. 1 below. Northeastern University will also waive the overhead on the industrial fees for the Center for Microcontamination Control.

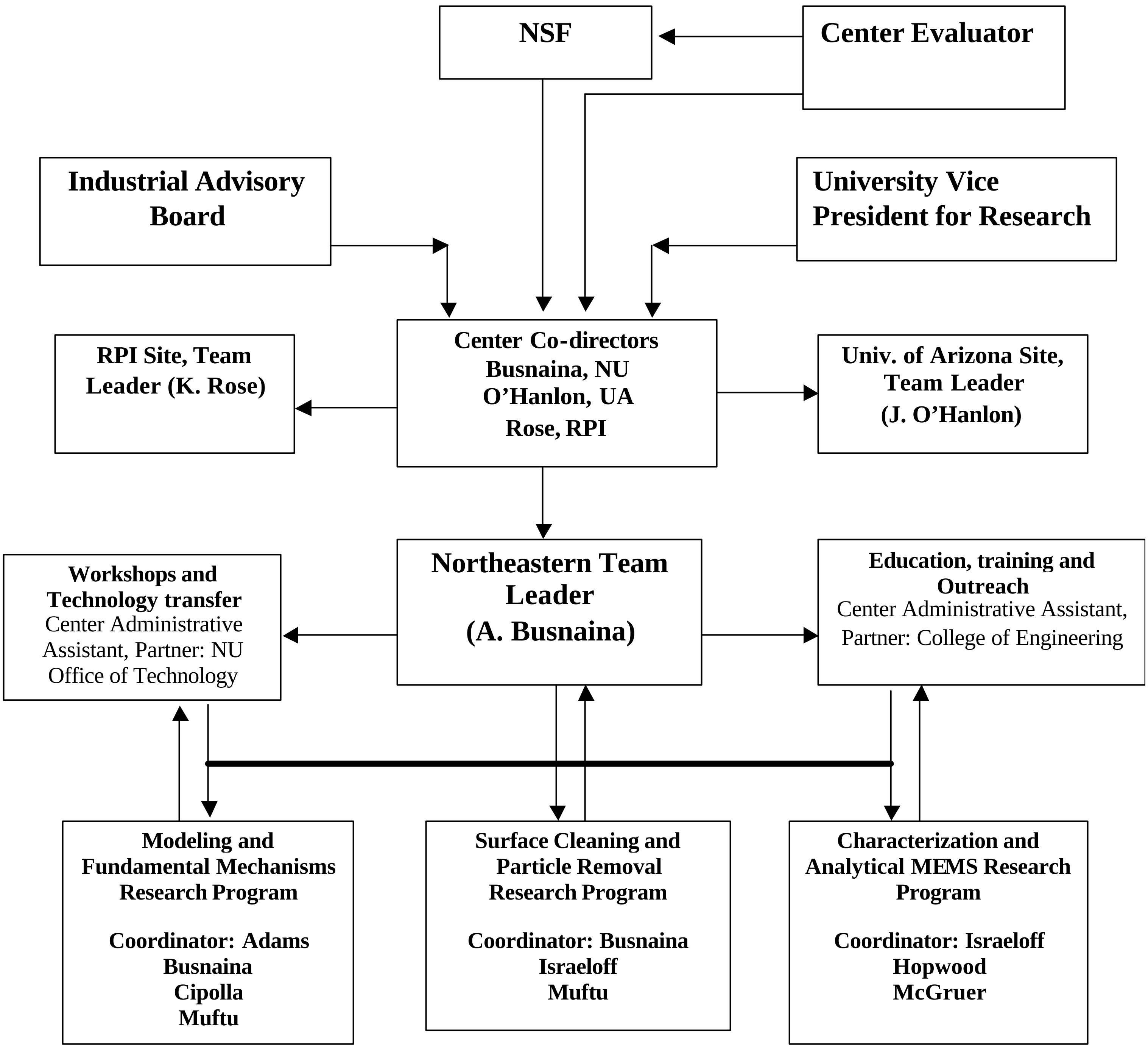


Figure 1. The Center's Structure Organization Chart

B.2 ENVISIONED RESEARCH PROGRAM

There will be three main research programs with a faculty coordinator for each area. The research programs are: modeling and fundamental mechanisms, surface cleaning and particle adhesion and removal , and characterization and analytical MEMs.

B.2.1 Modeling and Fundamental Mechanisms Research Program
Program Coordinator: Adams

The Center will develop techniques and strategies based on the fundamental understanding of surface cleaning and preparation. This can only be accomplished by developing an understanding of surface cleaning and particle adhesion and removal mechanisms.

Project 1. Physical Cleaning Of Submicron Trenches, a Modeling Study, Busnaina

Goals and Objectives

The objective of the proposed work is to identify and establish effective cleaning techniques for micro and nano scale trenches and vias with high aspect ratios using pulsating flow. Physical modeling will be used to study the contaminant removal process in submicron deep trenches. The effect of oscillating flow frequencies, velocity amplitude and trench width and aspect ration on the rinsing efficiency and rates will also be determined. The direction of the flow with respect to the trench will also be explored since preliminary data indicates that oscillating flow normal to the trench is superior to flow parallel to the trench.

Project Description

According to the International Technology Roadmap for Semiconductors [2], the industry will face the challenge of cleaning 100 nanometer trenches with high aspect ratio (30-60) in the next five years. Cleaning high aspect ratio deep trenches is challenging because of the need to rinse or remove contaminants from the bottom of the trench. Megasonic cleaning is known as one of the most effective techniques in blanket wafer cleaning. Busnaina *et. al.* have studied megasonic rinsing and cleaning process for blanket wafer[5] and provided both experimental and modeling results. Although megasonic cleaning is currently used in patterned wafer cleaning, the mechanism of megasonic cleaning process for patterned wafers is not well understood. In our previous research[6], simulation of pulsating flow passing a series of rectangular cavities has been verified and shows excellent agreement with the numerical and experimental results. Pulsating flow rinse shows a significant advantage in pattered wafer cleaning because the vortex oscillating mechanism enhances the mixing. In this paper, the removal of contaminants from high aspect-ratio submicron trenches using high frequency pulsating flow (megasonic rinse) is studied using physical modeling. The effectiveness was also found to be a function of Strouhal number, which quantifies the extent of pulsating convection relative to steady convection. However, the effects of aspect ratio, surface tension and pulse intensity have not been investigated numerically, and no experimental studies of contamination removal from trenches have been attempted.

The rinsing of a single wafer in megasonic cleaning tank is modeled. Figure 2 shows the experimental and numerical results of the removal of potassium and chloride ions from the blanket wafer surface. The agreement between experiments and simulation is good for both stagnant bath and megasonic rinse. The megasonic rinse flow dramatically reduces the rinsing time because the oscillation increases the transport rate of the contaminant.

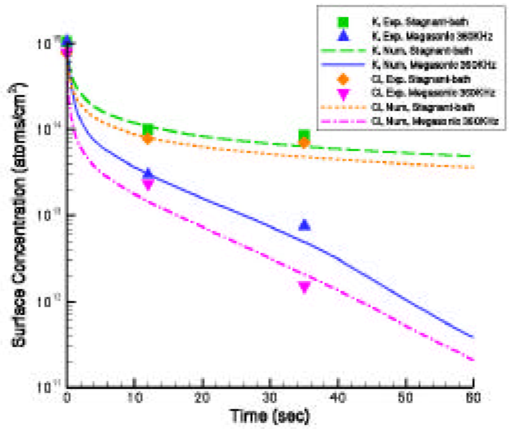


Figure 2. Potassium and chlorine contamination removal from blanket wafer surface

Patterned wafer cleaning can be modeled as a mass transfer in a pulsating flow past a series of rectangular cavities. The vortex oscillating mechanism introduced by the oscillating flow significantly enhances the mixing for cavities larger than 100 micron and the maximum mixing was found to depend on Strouhal number St=Wf/U_p, where W is the size (width) of the cavity, f the frequency, U_p the pulsating component of the rinse velocity, as shown in Fig. 3. For the two different size shallow trenches (AR=1:1, 1mm and 100 micron), the optimum St numbers are same (St=0.133).

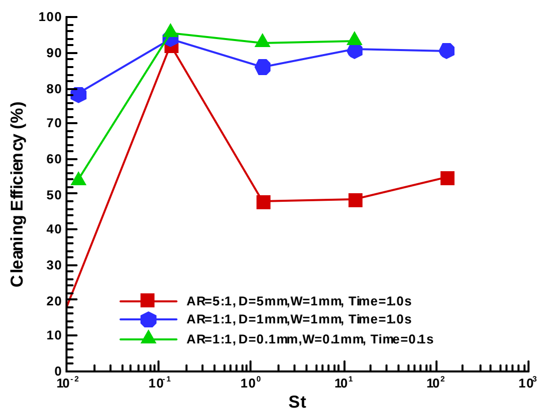


Figure 3. Effect of Strouhal number on cleaning efficiency

Project 2. The Mechanics of CMP and Post-CMP Cleaning, Muftu, Busnaina and Adams

Goals and Objectives

The goal of our activities is to conduct a detailed analysis of the mechanics of the CMP and post-CMP cleaning operations. To this end we will assess the applicability of the commercially available finite element programs and develop customized software models. This model will have the capability to bridge the fluid and solid mechanics at the macro level with the forces required to remove individual contaminant particles at the micro level.

Project Description

Contaminant particles adhere to the surface of a wafer due to adhesive and capillary forces. CMP and post-CMP cleaning processes consist of different methods that apply external forces to overcome the bonds between the contaminant particles and the wafer. The success of the cleaning operation i.e., removal of the particles depends on our ability to apply the necessary removal force on the particles. Particle removal operation involves the interactions of the forces in macro and micro length scales as depicted in Fig. 4. Surfaces of objects are typically rough with a seemingly random peaks and valleys [7]. Surface topography can be characterized by using contact (stylus) or non-contact (optical) profiling instruments. Characteristics of the surface topography are related to the manufacturing methods used in obtaining the surface. In general, when two objects are brought together contact initially occurs on the tallest asperities of the surfaces. As the normal force on the objects is increased these asperities deform and shorter asperities start to contact each other. The real contact pressure, p_r, that occurs over the individual asperities during this process can be integrated over the overall contact area, also known as the apparent contact area, to yield the apparent contact pressure, p_a. This relation is symbolically represented as $p_a = f(p_r)$. This function depends on the material properties of the surfaces as well as the statistical distribution of surface topography parameters. Greenwood and Williamson [8] gave such a relation assuming that deformation of each asperity forms a Hertzian contact [9]:

$$p_a = \frac{4}{3} h E_c R_p s_p \left(\frac{s_p}{R_p} \right) \int_d^{\infty} (s-d)^{3/2} f(s) ds$$

where d (= h/s_p) is the separation distance of the two surfaces, η is the asperity peak density, E_c, R_p and s_p are composite elastic modulus, asperity tip radii, and standard deviation of asperity peak heights. Normalized probability density function for the two surfaces is $f(s)$. Non-dimensional variable s is equal to z/s_p, where z is the measured surface height. Surfaces that display scale dependent surface height variation can be characterized by fractal analysis methods. Majumdar and Bhushan give a relation for predicting the contact pressure for fractal surfaces [10]. The contact pressure variation as a function of engagement height can also be measured experimentally. The relation between the real contact pressure and the apparent contact pressure, i.e., $p_r = g(p_a)$, can be similarly established. Then we can determine the amount of required external force in order to apply specified local contact forces over the asperities. The apparent contact pressure over the contact area results from the macro scale force equilibrium of the two contacting bodies. Polishing pads and rollers used in CMP and post-CMP applications are made of highly deformable porous materials. In analyzing the equilibrium of such materials large deformation elasticity theory and poroelasticity should be employed [11]. The cleaning process involves liquid which creates a lubrication layer in the interface and causes further deformation of the polishing pads or rollers, through a process known as elastohydrodynamic lubrication [12].

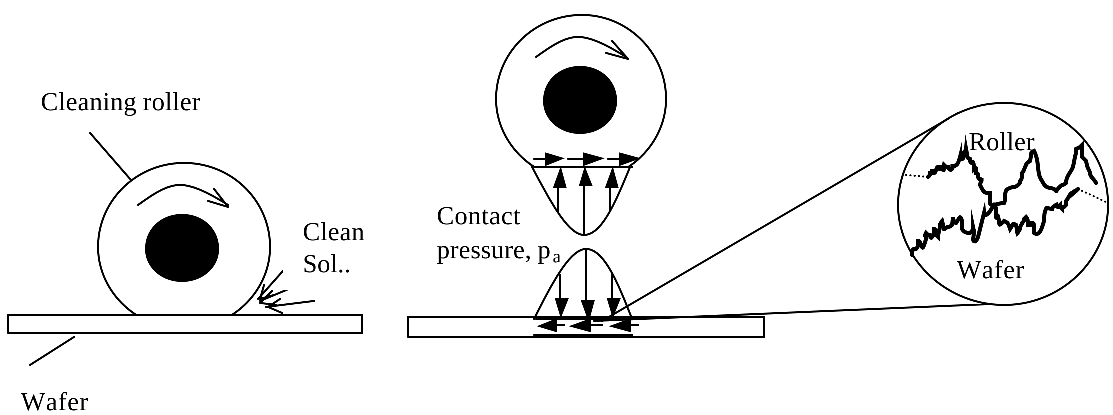


Figure 4. Different length scales are involved in a typical wafer polishing and cleaning operation.

Project 3. The Transport of Contaminants in Thin Film Deposition Processes, Cipolla, Busnaina and McGruer

Goals and Objectives

Identify and evaluate the effects of particle sources in low pressure processes. In addition, determine the effect of pressure and other process conditions on wafer contamination during wafer processing and handling. The elimination of particle sources will be studied using control by means of flow, electrostatics or geometrical design changes, and material selection.

Project Description

The particle transport and deposition from nucleation sites, process gas, and from the wall in a tungsten CVD cold wall reactor was investigated at pressure of 0.9 Torr. The study determined the particle deposition (for a size range of 10.0-0.05 micron particles) on the wafer and reactor wall, and the number of particles that exit the chamber with the gas. The model results were verified by experimental measurements. The study also determined the nucleation mechanism and the gas phase reaction that produces the tungsten silicide particles [13,14]. There is a definite need to evaluate transient conditions (including turbulence) significance to particulate and transport in thin film deposition processes (CVD, PVD, PECVD, etc.) and to determine the effect of diffusion, thermophoresis, thermal convection, electrostatics and non-ideal flow on particle deposition. Studies of CVD and PVD processes to investigate particle generation, transport and deposition and its effect on film deposition will be undertaken. Physical Models of the process gas, thermal field, particles, walls and all phenomena that may affect particles such as plasma, electrostatics, thermophoresis, and turbulence will be evaluated.

B2.2 Surface Cleaning and Particle Removal Research Program
Program Coordinator: Busnaina

The center will focus on surface cleaning of patterned, structured and flat substrates. Also the reduction of the use of chemicals in cleaning will be studied through the use of physical non-contact and/or contact cleaning, and the use of supercritical fluids, ozone and dilute chemistries. The adhesion force between particles and substrates will be investigated. Strong particle adhesion, which contributes to poor cleaning performance, is encountered in many applications such as CMP and post-CMP processes, wafer handling and many other applications where the adhesion increases with pressure, time, environmental conditions or chemical reactions.

Project 1. Nano and Microscale Particle Removal, Busnaina

Goals and Objectives

The objective of the proposed work is to develop an effective nanoscale particle removal technique using acoustic streaming. The study will provide an understanding of the removal mechanism that will be verified by experimental measurements and develop an effective process The results will be verified using semiconductor wafers with particles in the size range of 10-100 nm. The effect of streaming flow frequency, velocity amplitude and particle size and particle/substrate composition on the removal efficiency will also be determined experimentally and numerically.

Project Description

An era of the most challenging cleaning applications in nanofabrication and semiconductor manufacturing is upon us. The decreasing particle size down to the nano-scale level and its limiting effect on present surface cleaning techniques is critical. Theoretically, it can be shown that the removal of nano-size particles (10-100 nm) can be accomplished using acoustic streaming at frequencies larger than 1 MHz (typically referred to as megasonic frequency). One of the most important aspects of using acoustic streaming is the effect of the frequency on the boundary layer. As the frequency increases, the acoustic boundary layer thickness decreases and the streaming velocity increases. Both effects tremendously increase the drag force and consequently the particle removal moment. When the removal moment overcomes the adhesion moment, removal will take place. Experimental results show that complete removal down to 100 nm is possible. However, physical non-contact substrate and particle independent removal of nanoscale particles is not well understood and no commercial techniques exist in the industry today for the removal of such particles.

Busnaina *et al* [15-17,18,19] studied megasonic particle removal and the effect of acoustic streaming on many cleaning process especially in post-CMP applications. Gale and Busnaina have shown that cavitation implosion does not occur in megasonic cleaning and that the dominant cleaning mechanism is the acoustic streaming induced by the sound waves [20]. High particle removal efficiency on Si from megasonics in SC1 and SC2 solutions was also reported by Syverson, et. al.[21]. Again, removal increased with increasing power, up to a maximum tested value of 150 W. Wang, et. al.[22] performed experiments using megasonics for cleaning after RIE planarization. Of the parameters they tested, power had the greatest influence on the results.

The removal of nanoscale particles will be studied experimentally as well as using physical modeling. Experimental studies may include the use of fluorescent polystyrene spheres to quantify particle removal as well as the use of scanning Auger methods and electron microscopy to image particles. The fluid flow field and particle transport will be modeled using a solution of the governing momentum conservation, acoustic streaming equations with associated boundary conditions and particle adhesion and removal models. Particle removal from substrates will be simulated using oscillating flow at high frequency.

Project 2. Particle Adhesion and Removal for Post-CMP Applications, Busnaina, Adams and Muftu

Goals and Objectives:

The knowledge of the adhesion force and the onset of large adhesion force after polishing will lead to better cleaning and reduction of surface defects after polishing. The main objective of this project is study the removal and adhesion forces for alumina and silica slurry particles from silicon wafers using developed technique [23-25]. In addition, the effect of polishing on the slurry particle adhesion force will be determined.

Project Description

Slurry particle adhesion in post-CMP clean processes is a serious problem in the semiconductor industry. The current CMP removal rates models do not account for plastic deformation or particle adhesion between the particle and the wafer. Models have been developed to account for these important effects on polishing and cleaning [26-29]. However, particle adhesion measurements are needed to verify these models. These models are expected to be more fundamental and accurate in predicting CMP removal rate and the effect of the polishing process on the post clean process. There is a need for an effective post-CMP clean that is independent of the polished film or one that involves very dilute or no chemistry. Busnaina et al [15-20] studied ultrasonic and megasonic particle removal and the effect of acoustic streaming. In addition of the physical megasonic effect in removing particles, the use of chemistry has shown a big improvements in cleaning efficiency especially in post-CMP cleaning. In addition, the use of basic chemistry, reduces the total adhesion force and prevents the redeposition and readhesion of the removed slurry particles [33-34]. Gale and Busnaina indicated that SC1 removes more particles than DI water, particularly at lower megasonic powers. But they also demonstrated that it was possible to achieve 100 % removal in DI water using the optimum conditions. The industry is still having major difficulties in removing slurry particles. This is one of the biggest problem associated with the CMP process. This project will provide the conditions that give rise to large adhesion forces in addition to providing a better understanding of particle removal in post-CMP clean.

B.2.3 Characterization and Analytical MEMS Research Program
Program Coordinator: Israeloff

Project 1. Development of a MEMs Based Micro Gas Analysis System, Hopwood and McGruer

Goals and Objectives

The goal of this project is to develop a novel micro gas analysis system (MGA) consisting of a microplasma source for gas excitation, a microspectrometer to measure the atomic and molecular emission intensity, and an optical system coupling the light source and detector. The MGA will provide a compact, low-cost method for detecting gas impurities in semiconductor manufacturing.

Project Description

There is a need for reliable and accurate continuous monitoring of impurities in ultra pure gases used in semiconductor processing. The International Semiconductor Technology Roadmap calls for impurities such as H_2O, O_2, H_2, CO_2, CH_4, etc. to be monitored during gas delivery to many processes. Reliable and accurate continuous emission monitors (CEMs) are presently being developed to provide real-time information on the release of toxins from hazardous waste incinerators and the metal processing industry [30]. Perhaps the most mature technology for the continuous monitoring of airborne contaminants is inductively coupled plasma atomic emission spectroscopy (ICP-AES). This technique samples air from the environment, dissociates and electronically excites the air sample, and detects the photon emission from impurities using an optical spectrometer. ICP-AES has been used in analytical chemistry for quite some time using an argon ICP torch, but recent advances allow for accurate determination of impurities in air with detection limits (DLs) of a few $\mu g\text{-}m^3$, i.e., parts per billion [31,32]. These sensitive DLs are accomplished using background subtraction of a clean-air reference spectrum. Although current CEMs are capable of remarkable DL performance, the cost, size, and power requirements of the entire system preclude use in many applications. Here we describe progress toward creating a low-cost, low-power portable CEM using MEMS fabrication technology.

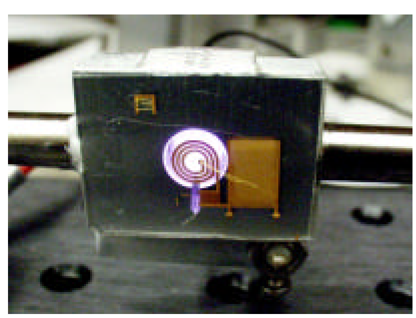


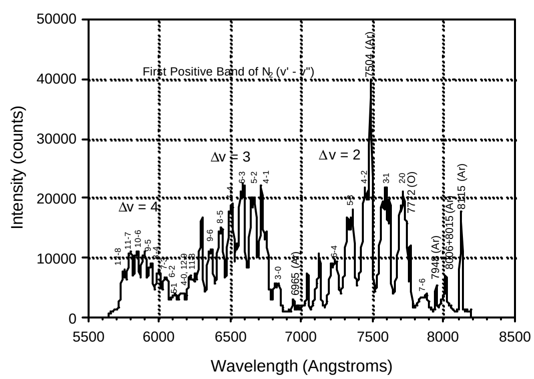
Figure 5. A micromachined inductively coupled plasma generator sustains an argon discharge. The coil shown at the center is 5 mm in diameter.

Laboratory-scale ICP-AES systems typically use an atmospheric-pressure plasma formed within a quartz tube that is several *cm* long and 2-5 *cm* in diameter. A water-cooled, helical coil wound around the tube couples radio-frequency energy (10-60 MHz, 1-2 kW) to the gas sample and forms a discharge. The relatively high pressure of the plasma allows three-body electron-ion recombination to occur within the interior of the discharge. This causes the plasma to constrict away from the walls of the plasma chamber. This constriction is critical because the atmospheric plasma is quite hot (T_{gas}~5000 K) and would damage the chamber walls if it were to contact them.

To miniaturize the ICP-AES concept and fabricate an instrument using MEMS techniques, modifications must be made to the plasma source. First, the plasma source will be operated at a reduced pressure. Lower pressure produces a nonequilibrium plasma in which the electron gas is much hotter than the atoms and molecules (T_e~30,000 K vs. T_{gas}~500 K). Optically-detectable excited states are still created by the energetic electron gas, but the relatively cool neutral and ion gases eliminate thermal management problems associated with the high-pressure, equilibrium plasma torches now in use. Second, the 3-D helical geometry of the ICP coil is difficult to microfabricate. We have replaced the large helical coil with a microfabricated flat, spiral-shaped coil that couples radio frequency energy into the plasma.

Large-scale optical spectrometers typically use diffraction gratings and long optical path lengths to resolve closely spaced emission wavelengths. The typical resolution of the instruments used in CEM is about 0.1 nm. Because these long path lengths are not compatible with MEMS

Figure 6. Optical emission spectrum obtained from an air microplasma showing trace amounts of argon.



technology, we have developed a small, micromachined Fabry-Perot interferometer. This type of spectrometer is quite suitable for microfabrication since it is essentially planar. Currently, the microspectrometer has a resolution of approximately 20 nm. Through improvements in the fabrication process and the development of feedback control, the resolution will be improved to ~1 nm. This resolution will result in a detection limit for the micro gas analyzer on the order of parts per million. The plasma generator is microfabricated by electroplating a gold spiral-shaped antenna and two interdigitated capacitors on a glass wafer [33]. The individual die are diced from the wafer and bonded to a 6-mm thick aluminum substrate that contains a 6-mm diameter cylindrical vacuum chamber as shown in Figure 5. The optical emission spectrum from an air plasma generated by this micromachined plasma source is shown in Fig. 6. The spectrum was acquired using an EG&G optical multichannel analyzer with a resolution of approximately 1 nm. The spectrum is dominated by the first positive band of molecular nitrogen. The trace amounts of argon that naturally occur in air (~0.9%), however, can clearly be seen in the spectrum as well. It is the goal of this project to detect trace amounts of gaseous impurities in high purity gases using an integrated microspectrometer. The Fabry-Perot microspectrometer selectively transmits a narrow band of wavelengths that are determined by the separation between to microfabricated mirrors. The mirror separation is mechanically scanned using electrostatic actuation between electrodes on the substrate and the cantilevered beams that support the upper mirror.

The microplasma source has been demonstrated using a 5 mm diameter antenna. To further decrease the size of the final instrument however, scaling the antenna to a diameter of 2 mm is currently underway. In addition, the operating conditions for the plasma source such as power, gas pressure, and chamber size will be optimized to increase the excitation intensity of various contaminants of interest to the semiconductor industry. Simultaneously, the microspectrometer's spectral resolution will be improved by pursuing improved mirror reflectivity, fabrication and assembly techniques, and electronic sensing and control.

Project 2. Characterization of Defects Due to Contamination, Israeloff

Goals and Objectives

The effect of contamination on nanoscale electrical transport, dielectric properties, and electronic noise will be studied. Transport and noise measurements will be made on nano and microscale wires and interconnects, in conjunction with AFM and STM imaging with the aim of characterizing the development of defects due to electromigration. The simultaneous study of resistance, electrical noise, and imaged defect development will be quite important to assessing the effect of contamination on circuit performance. The correlation of interconnects and wire failure with the measured properties and with material and fabrication techniques will guide fabrication processes.

Project Description

The project will focus on the micro and nanoscale physics of materials. Unique expertise in applying noise spectroscopy as a probe of defect dynamics, magnetism, superconductivity, and amorphous materials have been developed at Northeastern University. These techniques are based on atomic force microscopy (AFM) for probing nanoscale dielectric properties including dielectric susceptibility, noise and relaxation, and applied them to complex materials. Transport and noise measurements will be made on nano and microscale wires and interconnects, in conjunction with AFM and STM imaging with the aim of characterizing the development of defects due to electromigration. Professor Israeloff's current research focuses on the nanoscale physics of complex materials, such as polymer and organic glasses and copper oxides He has considerable expertise in nanoscale electrical transport [34], dielectric properties [35], electronic noise, and novel nanolithography techniques. [36] He has unique expertise in applying noise spectroscopy as a probe of defect dynamics [37], magnetism [38], superconductivity [39], and amorphous materials. [40-42] He has recently developed techniques, based on atomic force microscopy (AFM) for probing nanoscale dielectric properties including dielectric susceptibility, noise [42] and relaxation [35], and applied them to complex materials such as polymer glasses. [40, 41] He is developing these and related techniques into robust imaging, spectroscopy, and manipulation tools for the study of nanomaterials and nanostructures. There is a critical need for imaging and characterizing the nanostructures to be fabricated in the proposed research. Transport and noise measurements will be made on the narrow wires, in conjunction with AFM and STM imaging with the aim of characterizing the development of defects due to electromigration. The simultaneous study of resistance, electrical noise [43], and imaged defect development will be quite important. The correlation of wire failure with the measured properties and with material and fabrication techniques will guide the fabrication effort.

B.3 MANAGEMENT AND STAFFING PLAN

The proposed center at Northeastern University, University of Arizona and RPI organization structure chart is shown in section B.1. In addition to the faculty, the center administration will consist of the center director and an administrative assistant. The center director will be responsible for the management and administration of the center operational budget, maintaining a database of reports, records and publications, preparation of the annual report and completing of NSF surveys and reports. The director will also be responsible for the planning and implementing the center's long-term plans and monitoring research projects. The director will also be responsible for the marketing of the center to new companies, technology transfer, communication and coordination among the center co-directors and public relations.

An administrative assistant will perform basic secretarial and clerical duties with regard to the budget and the center internal operations as well as planning the annual meeting, industrial visits and faculty visits to companies. The proposed center evaluator will be Dave Tansik, who is currently the evaluator for the University of Arizona and RPI center. There will be three main research programs with a faculty coordinator for each area. The research programs are: modeling and fundamental mechanisms, surface cleaning, particle adhesion and removal, and characterization and analytical MEMs. Each research program and proposed project in each research area are listed in section B.2.

B.4 COST AND SOURCES OF FUNDING

The industrial funds in the form of membership fees ($40,000) will be used to support research projects to be adopted by the industrial advisory board. A list of potential industry supporters are listed in the next section. The NSF contribution of $50,000 will be used to administer the center and to cover the cost of the annual meeting, evaluation cost and communicate with the industrial members. The center will also conduct short courses and workshops and technology transfer in partnership with Northeastern's office of technology transfer. These short courses generate enough funds to cover the cost.

B.4.1 Potential of the Proposed Center to Obtain Industrial Funds

There is a strong potential for obtaining industry's support. Professor Busnaina has worked extensively with industry for the last 10 years. He obtained research funding from industry in excess of 3 million dollars. Ten letters of support from industry have been obtained and are enclosed in the supporting document Appendix. The companies are:

1. **Novellus Systems, San Jose, CA**
2. **Lam Research, Fremont, CA**
3. **ADE, Westwood, MA**
4. **Tokyo Electron America, Inc. Austin, TX**
5. **Cabot Microelectronics, Aurora, IL**
6. **Ultra Clean Technology Inc., Mountain view, CA**
7. **Eco-Snow Systems, Livermore, CA**
8. **EKC, Hayward, CA**
9. **SC Fluids Corporation, Nashua, NH**
10. **PCT Incorporated, Fremont, CA**

Companies that expressed support but did not provide a letter before the deadline:

1. **Praxair, Tonawanda, NY**
2. **Axcelis Technologies, Inc., Beverly, MA**

B.4 EVALUATION PLAN

The proposed center will utilize the same evaluation plan used at the University of Arizona and RPI center. In addition, center evaluator will be Dave Tansik, who is currently the evaluator for the University of Arizona and RPI center.

C. PROJECT DESCRIPTION

C.1 OBJECTIVES OF THE PLANNING GRANT

The objective of the planning meeting is to bring together potential industrial members faculty and students to focus and discuss the research focus and needs, proposed research projects and to obtain letters of commitment. The proposed meeting is outlined in section C.2. During the breakout sessions (during the first day) after the research focus and research projects presentation, the faculty and the industrial members will discuss the research focus and to elicit input from industrial members regarding the proposed research program and projects. The discussions will also continue during informal social interaction in the evening. Copies of the research proposals for each project and supporting documents will be distributed prior to the meeting. All research proposals will be evaluated after each presentation using NSF IUCRC Level of Interest Feedback Evaluation (LIFE) forms which will be distributed prior to the meeting. In addition, potential industrial members will be encouraged to suggest research ideas that may be transformed into research proposals that may be added to the proposed projects. During the second day, discussion will deal with the research focus and projects as well as the center policies regarding intellectual property, publications and level of funding will also be discussed

The planning meeting main goal is to present the research proposals and open a forum to discuss research ideas and formalize the potential industrial members feedback. The collected feedback will be discussed during the meeting in the breakout session and project feedback sessions during the second day. Potential Industrial sponsors will be asked to identify their research priorities, provide research input, and indicate current and future needs of the industry. Industrial input on research projects is necessary to the success of the Center.

C.2 OUTLINE OF THE CENTER FOR MICROCONTAMINATION CONTROL PLANNING MEETING

6:00-7:30 P.M.	Meeting Registration
7:30-9:30 p.m.	Informal Cocktail Reception and Discussion
First Day	
7:00-8:30 a.m.	Breakfast
8:45-9:00 a.m.	Welcome – Vice Provost for Research of Northeastern University Introduction to Northeastern University
9:00-9:1 0 a.m.	Introduction of Participants
9:10-9:30 a.m.	Introduction to the Mechanical, Industrial and Manufacturing, Electrical and Computer Engineering and Physics Departments
9:30-10:10 a.m.	Center Structure: presentation by Center Co-Directors assisted by a key industrial supporter outlining the need for the proposed research of the proposed center and describing the organization including major policies and procedures, cost and funding options. (Busnaina, O'Hanlon and Rose)
10:10-10:50 a.m.	Research Program: presentation by the director of the proposed research focus of the center. (Busnaina)
10:50-11:20 a.m.	Coffee Break
11:20-11:40 a.m.	Introduction to NSF IUCRC Program (Schwarzkopf)
11:40-11:55 a.m.	Presentation by the evaluator regarding evaluation procedures and feedback during the meeting, what is envisioned for semi annual meetings, and the administration of the NSF research instruments to gauge measures of intervening center success. (Tansik)

11:55-12:00a.m.	Outline of the afternoon session.
12:00-1:00 p.m.	Lunch
1:00-1:45 p.m.	Modeling and fundamental mechanisms Research Program: Overview of research by the coordinator (Adams) followed by 15 minutes project presentations; use proposal and Level of Interest Feedback Evaluation (LIFE) forms.
1:45-2:30 p.m.	Surface Cleaning, Particle Adhesion and Removal Research Program: Overview of research by the coordinator (Busnaina) followed by 20 minutes project presentations; use proposal and LIFE forms.
2:30-3:15 p.m.	Characterization and Analytical MEMs Research Program: Overview of research by the coordinator (Israeloff) followed by 20 minutes project presentations; use proposal and LIFE forms.
3:15-3:45 p.m.	Coffee Break
3:45-5:00 p.m.	Breakout Sessions by Research Area. Guided discussion and feedback on the proposed projects-use Discussion Guide.
5:00-5:30 p.m.	Discussion of the organization of the evening and morning session. Use Organization Feedback Form
6:00-7:30 p.m.	Cocktail Hour and Dinner
7:30- 8:30 p.m.	Discussion of Project Feedback (Busnaina and Gotkis, Lam research) Review and discussion of feedback obtained via LIFE forms and during breakout sessions. Focus on kinds of changes and refinements for which there is a consensus.

Second Day

7:00-7:30 a.m.	Breakfast
7:30-8:30 a.m.	Discussion of Organizational and Policy Feedback (Busnaina and Gotkis, Lam research). Closing Remarks, Action Items.

C.4 LEADERSHIP OF THE CENTER (Managerial Experience of the Director)

Professor Ahmed Busnaina will be the co-director of the center at Northeastern University joining the current co-directors of the Center for Microcontamination Control, professors John O'Hanlon of the University of Arizona and Kenneth Rose of RPI. The proposed center will work jointly with the existing Microcontamination Control Center at University of Arizona and RPI. The industrial members at all three sites will share the research results of all the sites.

Professor Busnaina, the William Lincoln Smith Professor and Director of the Microcontamination Research Laboratory at Northeastern University, has an extensive experience in managing research projects funded by industry and participated in three research centers that were mostly funded by industry. He Established the Microcontamination Research Laboratory at Clarkson Univ. in 1988 including a fully equipped class 10 cleanroom, to provide innovative basic and applied research to the semiconductor industry and equipment manufacturers. This class 10 cleanroom was the first of its class at a university in the U.S. to be used for microcontamination research. In January 1991, Prof. Busnaina established an industry/university cooperative research center "Center for Particulate Control in Process Equipment (CPC)." The center operated for six years before the university folded the center in the Center for Advanced Materials Processing. Several faculty members from different departments have participated in the center's multidisciplinary research program. The Center was fully supported with industrial funding in the form of membership fees, equipment lease and donation. He had a strong interaction with industry for the past 15 years. He obtained more than five million dollars in research funding, sixty percent of which came from industry. He received support from the following companies and agencies: IBM, Intel, Motorola, Eaton Corp., Praxair, Verteq, IPEC, FSI, Corning, GE, Crest, SSEC, Seagate, VLSI Logic, Kodak, Xerox, SRC, Sematech, NSF and Lawrence Livermore National Laboratory.

References

1. Hattori, T., "Contamination Control: Problems and Prospects," Solid State Technology, vol. 33, no. 7, p s1 (July 1990).
2. The National Technology Roadmap for Semiconductors Technology Needs, The Semiconductors Industry Association. 2000.
3. Lin, H.; Busnaina, A. A.; Suni, I. I., Physical Modeling of Rinsing and Cleaning of Submicron Trenches, *Proceedings of the IEEE 2000 International Interconnect Technology Conference*, pp. 49-51 (June, 2000).
4. Lin, H, Busnaina, A. A. and Suni, I, "Modeling of Rinsing and Cleaning of Trenches." International Sematech Wafer Cleaning and Surface Preparation Workshop 2000, April 11-12, 2000, Austin TX.
5. Busnaina, A. A. and Gale, G. W, *Journal of Particulate Science and Technology,* 17(3), 1999.
6. Lin, H., Busnaina, A. A. and, and Suni, I. I., proceeding, *IITC 2000*, San Francisco, CA, June 2000.
7. Rabinowicz, E. (1995), Friction and Wear of Materials, John Wiley & Sons, NY.
8. Greenwood, J.A., Williamson, J.B.P., (1966), ``Contact of Nominally Flat Surfaces," Proc. Royal Soc. of London Series A, Vol. 295, pp. 300-319.
9. Johnson, K.L., (1985), Contact Mechanics, Cambridge University Press, Cambridge, UK.
10. Bhushan, B., (1999) ed. Handbook of Micro/Nano Tribology, 2nd edition, CRC Press, Boca Raton, Florida.
11. Malvern, L.E. (1969), Introduction to the Mechanics of a Continuous Medium, Prentice-Hall, New Jersey.
12. Hamrock, B.J., (1994), Fundamentals of Fluid Film Lubrication, McGraw-Hill, New York.
13. MacGibbon, B.S., Busnaina, A. A., and Fardi, B., "The Effect of Thermophoresis on Particle Deposition in a Low Pressure Chemical Vapor Deposition Reactor," *J. of the Electrochemical Society, Solid State Science and Technology,* Vol. 146, No. 8, 1999.
14. MacGibbon, B.S., Busnaina, A. A. and Rasmussen, D. H., "Particulate Contamination in Tungsten LPCVD: An Experimental Study," *Journal of American Vacuum Science and Technology B*, 17(2), Mar/Apr, 1999.
15. Busnaina, A. A., Kashkoush, I. I., and Gale, G. W., "An Experimental Study of Megasonic Cleaning of Silicon Wafers," *Journal of Electrochemical Society*, vol. 142, No. 8, August 1995, pp. 2812-2817.
16. Gale, G. W. and Busnaina, A. A., "Removal of Particulate Contaminants Using Ultrasonics and Megasonics: A Review," *Journal of Particulate Science and Technology*, vol. 13, 1995, pp. 197-211.
17. Busnaina, A. A. and Gale, G. W, "Removal of Silica Particles from Silicon Substrates Using Megasonics Cleaning," *Journal of Particulate Science and Technology*, Vol. 15, 1997.
18. Busnaina, A. A., and Dai, F., J. Adhesion, vol. 67, 1998, pp. 181-193, 1997.
19. Busnaina, A. A. and Elsawy, T. M., "Post-CMP Cleaning Using Acoustic Streaming," Journal of Electronic Materials, Vol. 27, No. 10, pp. 1095-1098, 1998.

20. Busnaina, A. A. and Gale, G. W, "Roles of Cavitation and Acoustic Streaming in Megasonic Cleaning," *Journal of Particulate Science and Technology*, Vol. 17, No. 3, pp. 229-238, 1999.
21. Syverson, W., Fleming, M., and Schubring, P., *Second International Symposium on Cleaning Technology in Semiconductor Manufacturing*, Electrochemical Society Proceedings PV92-10, p. 10 (1992).
22. Wang, P., and Bell, D., *Third International Symposium on Cleaning Technology in Semiconductor Device Manufacturing*, Electrochemical Society Proceedings PV94-7, p. 132 (1994).
23. Busnaina, A. A., Taylor, J. and Kashkoush, I.,"Measurements of Adhesion and Removal Forces of Submicron Particles on Silicon Surfaces, " *Journal of Adhesion Science and Technology*, vol. 7, No. 5, 1993, pp. 441_455.
24. Rimai, D. S. and Busnaina, A. A., "The Adhesion and Removal of Particles from Surfaces," *Journal of Particulate Science and Technology,* vol. 13, 1995, pp. 249-270.
25. Krishnan, S., Busnaina, A. A., Rimai, D. S. and DeMejo, D. P., "The Adhesion-induced Deformation and the Removal of Submicrometer Particles," *Journal of Adhesion Science and Technology*, vol. 8, No. 11, 1994, pp. 1357_1370.
26. Zhang, F. and Busnaina, A., "Particle Adhesion and Removal in Chemical Mechanical Polishing (CMP) and post-CMP Cleaning," *Electrochemical and Solid-state Letters,* (in press), 1999.
27. Zhang, F. and Busnaina, A.A., "Particle Adhesion Force in CMP and Subsequent Cleaning Processes," *Proceedings of the VLSI Multilevel Interconnection Conference (VMIC),* Santa Clara, CA, February 8-12, 1999.
28. Zhang, F. and Busnaina, A. A., "The Effect of Particle Adhesion on Chemical Mechanical Polishing (CMP) Removal Rate an Post-CMP Cleaning," The Adhesion Society Proceedings, 21st Annual Meeting, Panama City, FL, February 21-24, 1999.
29. Zhang, F. and Busnaina, A., "The Role of Particle Adhesion and Surface Deformation in Chemical Mechanical Polishing," *Electrochemical and Solid-state Letters,* Vol. 1, No. 4, October 1998.
30. Gerhard A. Meyer and Michael Seltzer, "Continuous ICP measurement of hazardous metals in stack gas emissions," American Laboratory, vol. 29, pp. 34L, 1997.
31. Anne-Marie Gomes, Jean-Phillipe Sarrette, Lydie Madon, and Abdenbi Almi, "Continuous emission monitoring of metal aerosol concentrations in atmospheric air," Spectrochim. Acta B, vol. 51, pp. 1695-1705, 1996.
32. Michael D. Seltzer and Robert B. Green, "Instrumentation for continuous emissions monitoring of airborne metals," Process Control and Quality, vol. 6, pp. 37-46, 1994.
33. J. Hopwood, O. Minayeva, and Y. Yin, "Fabrication and Characterization of a Micromachined 5 mm Inductively Coupled Plasma Generator," accepted for publication, J. Vac. Sci. Technol. B, vol. 18, Sept/Oct 2000.
34. N. E. Israeloff, F. Yu, A. M. Goldman, R. Bojko, "Nonlocal paraconductance of small superconducting loops", *Phys. Rev. Lett.* 71, 2130 (1993).
35. L. E. Walther, N. E. Israeloff, E. Vidal Russell, and H. Alvarez Gomariz, "Mesoscopic Scale Dielectric Relaxation at the Glass Transition", *Phys. Rev.* **B57** (Rap. Comm.), R15112 (1998).
36. N. E. Israeloff, G. B. Alers, M. B.Weissman,"Spin-fluctuation statistics in CuMn", *Phys. Rev.* B 44, 12613 (1991).
37. C. E. Parman, N. E. Israeloff, J. Kakalios, "Random telegraph-switching noise in coplanar current measurements of amorphous Si", *Phys. Rev.* B 44, 8391 (1991).
38. N. E. Israeloff, M. B. Weissman, G. J. Nieuwenhuys, "Electrical noise from spin fluctuations in CuMn", *Phys. Rev. Lett.* 63, 794 (1989).

39. Charles Surya, N. E. Israeloff, A.Widom, R. Seed, C. Vittoria, "Flicker noise in YBa[sub 2]Cu[sub 3]O[sub 7 - delta] bicrystal grain boundary, Josephson junctions", *Appl. Phys. Lett.* 67, 1307 (1995).
40. E. Vidal Russell, N. E. Israeloff,L. E. Walther, H. Alvarez Gomariz, "Nanometer Scale Dielectric Fluctuations at the Glass Transition, *Phys. Rev. Lett.* 81, 1461 (1998);
41. E. Vidal Russell, N.E. Israeloff,"Direct Observation of Molecular Cooperativity at the Glass Transition", *Nature* (in press, 2000).
42. L. E. Walther, N. E. Israeloff, E. Vidal Russell, and H. Alvarez Gomariz, “Atomic Force Measurement of Low Frequency Dielectric Noise”, *Appl. Phy. Lett.* **72**, 3223 (1998).
43. B. Alers, N. L. Beverly, A. S. Oates,” Electromigration in isolated aluminum vias probed by resistance changes and 1/f noise, G., *J. Appl. Phys.* 79, 7596 (1996).