VACUUM MECHATRONICS

Susan Hackwood, Steven E. Belinski and Gerardo Beni

Center for Robotic Systems in Microelectronics
University of California, Santa Barbara

Abstract

The discipline of vacuum mechatronics is defined as the design and development of vacuum-compatible computer-controlled mechanisms for manipulating, sensing and testing in a vacuum environment. The importance of vacuum mechatronics is growing with an increased application of vacuum in space studies and in manufacturing for material processing, medicine, microelectronics, emission studies, lyophylisation, freeze drying and packaging. The quickly developing field of vacuum mechatronics will also be the driving force for the realization of an advanced era of totally enclosed clean manufacturing cells. High technology manufacturing has increasingly demanding requirements for precision manipulation, *in situ* process monitoring and contamination-free environments. To remove the contamination problems associated with human workers, the tendency in many manufacturing processes is to move towards total automation. This will become a requirement in the near future for e.g., microelectronics manufacturing. Automation in ultra-clean manufacturing environments is evolving into the concept of self-contained and fully enclosed manufacturing. At the CRSM we are developing a Self Contained Automated Robotic Factory (SCARF) as a flexible research facility for totally enclosed manufacturing. The construction and successful operation of a SCARF will provide a novel, flexible, self-contained, clean, vacuum manufacturing environment. SCARF also requires very high reliability and intelligent control. In this paper we will review the trends in vacuum mechatronics and discuss some of the key research issues.

1. Introduction

Vacuum mechatronics involves the design and development of vacuum compatible computer controlled mechanisms for manipulating, sensing and testing in a vacuum environment. Vacuum mechatronics is becoming important due to the increased use of vacuum in applications for space studies and manufacturing for material processing, medicine, microelectronics, emission studies, lyophylisation, freeze drying and packaging. As the benefits of the vacuum environment, e.g. low pressure, long mean free path length and cleanliness, become better defined and understood, the desire to implement more processes in vacuum will increase. The vacuum environment is therefore important in many operations requiring a controlled, contamination-free environment.

Vacuum mechatronics plays a particularly important role in the microelectronics industry. Microelectronics manufacturing has increasingly demanding requirements for precision manipulation, *in situ* process monitoring and contamination-free environments. To remove the contamination problems associated with human workers, there is a need to move towards total automation for IC manufacturing. This will become a requirement in the near future as dimensions decrease below 1μm and circuit complexities increase. There is also a trend toward the use of self-contained manufacturing systems since clean rooms are no longer adequate. It has been shown that vacuum, once achieved, is inherently superior to the best clean room environments. Automation in ultra clean manufacturing environments is evolving into the concept of self contained and fully enclosed manufacturing. At the CRSM we are developing a Self Contained Automated Robotic Factory (SCARF) as a flexible research facility for totally enclosed manufacturing. The SCARF system will be used for prototyping application-specific IC's (ASIC's) e.g., 1μm CMOS and NMOS. The construction and successful operation of a SCARF will provide a novel, flexible, self contained, clean manufacturing environment. A self contained manufacturing environment is appealing for IC manufacturing as it allows the implementation of fast cycle times, high yield, low cost and flexible prototyping. It also requires very high reliability and intelligent control. Already, a number of equipment manufacturers have chosen to isolate processes in self-contained vacuum environment manufacturing cells, using small robots as wafer transfer devices (e.g. Applied Materials Precision 5000 Etch, Precision 5000 CVD and 9000 Ion Implanter, Varian 5103 CVD system and M2000 Sputtering System). Such systems take advantage of the superior cleanliness properties of vacuum and indicate the eventual direction of microelectronic (and other cleanliness-intensive) manufacturing.

Many manufacturing steps are understandably dependent upon atmospheric pressure conditions, especially those which presently require an operator. Total in-vacuum manufacturing systems will not be realized unless a concentrated effort is made to develop and *integrate* the vacuum-compatible system components. These include robots, sensors, vision inspection systems, particle detectors and various testing and measuring devices. In the following sections we will discuss some key research problems in vacuum mechatronics and describe ongoing research projects in this area.

2. Vacuum Mechatronics: Scope and Goals

a. Vacuum Mechatronic Applications

Vacuum can be classified into natural (space) and artificial (vacuum chamber). Vacuum, as an environment for various processes, can provide many advantages over an atmospheric environment, such as low particle contamination level, collision-free space, and long monolayer forming time [1]. These properties are currently used in advanced research projects in particle physics, material science, microelectronics, biotechnology, etc. There are opportunities for developing new vacuum systems for these fundamental technologies. However, it is the applications of vacuum mechatronics to manufacturing are becoming interesting. From the time of the first artificial closed vacuum systems, there has undoubtedly been a desire to manipulate objects inside the chamber with as much ease as those outside the closed system.

The space program has provided much of the forward momentum in vacuum mechatronics due to the numerous vacuum problems which had to be solved for space missions [2]. Some of these solutions have recently been applied and extended for use in chamber-based production environments, such as those used for coating (e.g. evaporation or sputtering). In this and other vacuum production applications, the transfer and/or positioning functions provided by the mechatronic equipment is critical to the overall process.

b. Vacuum Mechatronics Design

Mechatronics design for vacuum poses design constraints on the selection of materials, choice of lubricants and on modes of energy transfer [3,4]. Materials should have the standard design properties e.g machinability and ease of fabrication etc., and in addition must have surface vapor pressures lower than the operating pressure and temperature. Desirable physical properties of lubricants for vacuum include low vapor pressure over a wide temperature range, low contamination level and low coefficient of friction. Energy transfer in vacuum needs to focus on heat dissipation and energy input to a mechanism in vacuum. Natural convection is absent in vacuum and thus dissipation must be achieved by conduction, radiation or forced convection.

The effective use of the vacuum environment will depend on the availability of these vacuum components. Mechanisms and machine design research should include joints, bearings, energy transmission/control devices, linkages, fasteners, etc. for vacuum [5,6]. Actuators e.g., vacuum rated motors, piezoelectric devices will need to be developed. The need for and methods of sensing in vacuum (e.g., encoders for vacuum motors, force sensors, vision sensors) will also be needed.

An intelligent controller which can deal with limited sensory information/limited control action possessing fault detection/tolerance capability must be designed for vacuum mechatronics control [7]. Real-time multi-sensory data fusion is desired[8,9]. A computationally very efficient world model is important, because it can be used with active sensing, in working space understanding and model adaptation, as well as in the expectation and sensory data interpretation during operation.

Since the usual teaching method is no longer adequate for vacuum mechatronics, real-time simulation capability is highly desirable to assist program control. Some new criteria for optimal trajectory and task scheduling must be introduced. Reliability is another important issue in vacuum mechatronics, besides component design, emphasis must also be placed on the controller, i.e., fault tolerance ability, since frequent repair is undesirable.

c. System Design and Integration

Although there are many problems inherent in system design common to both atmospheric and vacuum applications, there are problems associated with designing mechatronic systems for vacuum that warrant special attention. Outgassing, heat transfer, and particle emissions are issues that must be addressed in vacuum work [10,11]. Reliability, always a concern when designing mechatronic systems, becomes especially important when the system is enclosed in a vacuum chamber. The overall size of the finished system can be very important in vacuum applications. Often systems must be constructed to fit into existing vacuum chambers; in any case the size of the system and therefore the surrounding chamber must be kept small to keep the costs of the chamber and pumping system down. Another difficulty in designing mechatronic systems for vacuum use is a lack of vacuum compatible subassemblies (e.g. robots, stages, etc.), the building blocks of system design.

3. Vacuum Mechatronics: Current Research Projects

The current research program at the CRSM is focussed in three areas:

1: **INTELLIGENT SYSTEM DESIGN, SIMULATION AND CONTROL**
    VACUUM-COMPATIBLE ACTUATORS
    VACUUM ROBOTS
    SELF-CONTAINED SYSTEMS
2: **SENSORS IN VACUUM**
    VISION
    MULTIPLE SENSING SYSTEMS
3: **IN-VACUUM CLEANLINESS AND PARTICULATE CHARACTERIZATION**
    MEASUREMENT TECHNIQUES
    MECHANISM TESTING

Several of these research projects will be discussed in more detail below. In particular, the development of vacuum compatible robots, self contained systems, vision and particulate characterization will be described.

3.1 INTELLIGENT SYSTEM DESIGN, SIMULATION AND CONTROL

VACUUM-COMPATIBLE ACTUATORS

New Actuator Design

Application of conventional electric motors in vacuum leads to problems. At high vacuum the gas density is so low that conduction and convection can no longer take place, thermal exchange is carried out mainly by radiation. If power is applied to a motor in vacuum, and no sink is provided, it will heat up until losses due to radiation cause an equilibrium. A temperature of 125°C can be reached in several minutes with the application of the maximum rated voltage to a thermally isolated motor. This problem may be minimized by designing appropriate heat sinking, limiting the voltage necessary to drive the load and reducing or eliminating the holding current when the motor is not running[12]. Even if the temperature effects are controlled, the motor must be constructed of suitable materials and employ appropriate lubrication. The CRSM is cooperating with Yaskawa Electric to develop motors specifically for high-vacuum robot applications. They have been developing an axial gap pulse motor, which will withstand temperatures to 300°C and vacuum levels of 10^{-11} Torr[13].

Magnetically Levitated Systems for Clean Vacuum Operation

Magnetically levitated systems have great potential for vacuum applications[14]. Lack of surface contact in such devices can reduce the particle load significantly.

Motion Control for In-Vacuum Motors

Some unique considerations exist with respect to the control of in-vacuum motors. Due to the lack of conduction through air and convection in a vacuum, optimized temperature control is desirable. Also, the currently available vacuum motors are of the stepper motor variety, making feedback control and smooth motion difficult for precision actuators and robots.

VACUUM ROBOTS

Vacuum Robot Development for Industrial Manufacturing

A robot capable of operating in high vacuum (to 10^{-7} Torr) has been developed for ultra-clean manufacturing of gyroscopes in a self contained manufacturing environment. This was a two year effort in collaboration with Delco Systems Operations. The availability of vacuum-compatible robots is presently limited, although this is likely to change in the near future[15]. A modified commercially available robot was used for use in the assembly task[16]. Although it is desirable to use a robot which was designed and built specifically for the vacuum environment, the first step was to obtain a vacuum-compatible robot.

The vacuum robot is a GMF model E-310 cylindrical coordinate robot, originally designed for use in clean rooms to class 10. The principal design requirements for the modification of the GMF E-310 robot for vacuum compatibility were:

- Modification of axes movement range:
  - Z-axis: maintain 300mm stroke if possible
  - R-axis:maintain 500mm stroke if possible; if reduced, resulting stroke must be useful in the vacuum chamber
  - q-axis: maintain ±150° rotation
  - a-axis: maintain ±180° rotation
- Limit negative effects on the vacuum environment (outgassing, etc)
- Design for ≤ 100°C operating environment

The first decision in the modification of the GMF E-310 was between two methodologies. The robot could either be totally exposed to the vacuum environment or it could be sealed in a type of "suit" which would allow the inside components to operate at atmospheric pressure, as they were originally designed to do. In order to expose the entire robot to a pressure of 10^{-8} Torr, a number of key changes would have to be made. The major ones would be in the lubrication systems, the surface finish and materials, and the motors. After examining this choice, it was concluded that it would entail a substantial amount of redesign work, and that a total exposure robot would be better designed from scratch. The goal then became one of designing a new housing for the robot which would seal it from the vacuum environment, while accomplishing the design goals. The sealing "suit" would have to be as leak-tight as the walls of a high-quality vacuum chamber, yet must also allow the desired motions by sealing two linear (R and Z) and two rotary (Theta and Alpha) motions. The completed robot is shown in Figure 1.

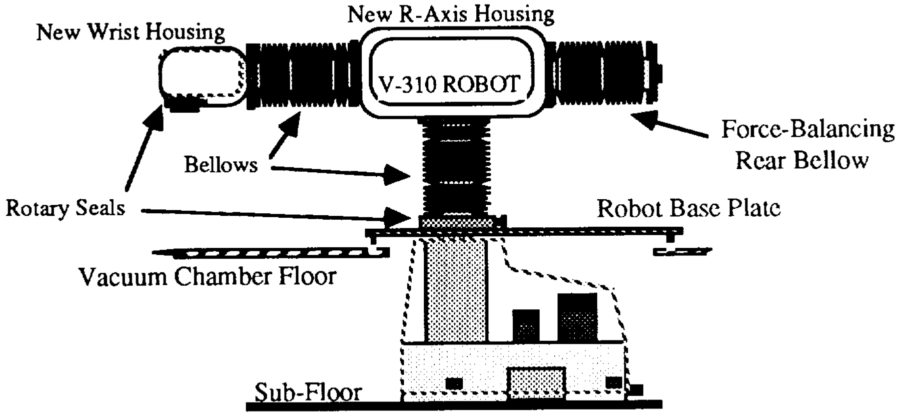

Figure 1. Modified E-310 Vacuum Robot

SCARF Vacuum Robot and Controller Development

The modified GMF vacuum robot described above is useful, but is not ideal. A robot designed to be fully exposed to the vacuum is more difficult to build but has greater implications for vacuum mechatronics. The CRSM, in cooperation with Yaskawa Electric, has designed and built a vacuum-compatible robot for use in the SCARF vacuum chamber (Figure 2). The robot has many advanced features not currently found in the small vacuum-compatible pick-and-place robots used in microelectronic processing stations. Some key features are:

- The robot is of cylindrical coordinate design, with a linear reach axis. This configuration is inherently suited to a *cylindrical* vacuum chamber.
- The robot's stepper motors are completely vacuum-compatible and use vacuum-compatible magnetic encoders. This eliminates the need for any motion feedthroughs, which are potential leak sources. It also allows for a significant vertical stroke (120mm) which is missing in other vacuum robots due to the sealing problems of a linear feedthrough.
- The controller is based on the Motorola 68020 processor and the TMS320 digital signal processor, and fully programmable in a high level Pascal-like language.
- The controller is easily interfaced to a host computer. The robot then falls under the authority of the overall system controller, easing system integration.

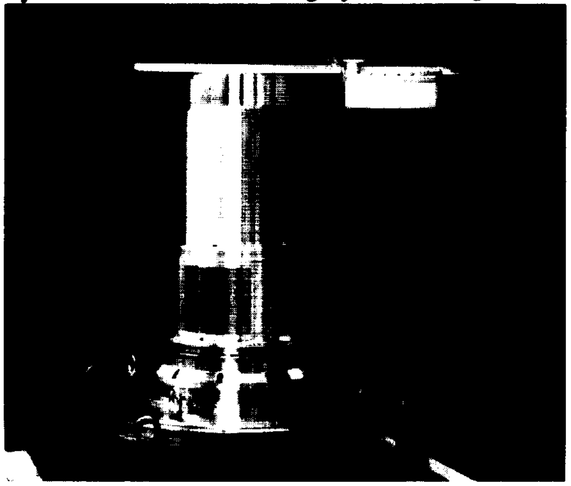

Figure 2. SCARF Robot

Basic specifications are as follows:

	TRAVEL RANGE	RESOLUTION	REPEATABILITY	MAX SPEED
S-axis: (base rotation)	360°	.013°	±.013°	90°/s
Z-axis: (vertical stroke)	120mm	0.1mm	±0.1mm	60mm/s
H-axis: (horizontal stroke)	657.66mm	0.25mm	0.25mm	250mm/s
W-axis: (off-robot wafer rotation)	360°	0.25°	±0.25°	90°/s
Payload:	0.4kg			
Vacuum Compatibility:		• Vacuum-compatible to 10^{-7} Torr • Total leak rate less than $5x10^{-9}$ Torr liters/s He • Bakeable to 100°C		

Table 1. SCARF Robot Specifications

SELF-CONTAINED SYSTEMS

Vacuum Mechatronics in the IC Processing Environment.

The semiconductor industry is rapidly evolving to produce the high variety and short cycle times demanded by its customers. Application Specific Integrated Circuits (ASIC's) are proliferating [17,18]. As the demands for flexibility increase, the fabrication process sequences themselves are becoming longer with more levels and complexity. Dimensions and design rules are expected to be reduced below 0.5 µm in the next few years. The corresponding allowable particle sizes (using the one-tenth rule) are less than 500Å. Not only can we not directly measure these sizes, but present day clean rooms have approximately a $1/d^2$ law for particle densities vs. particle sizes [19] and therefore very large densities of small particles cannot be avoided by using currently designed airborne clean room systems.

It was clear even in the early 80's that an integrated manufacturing capability would be needed by the microelectronics industry [20]. By early 1987, several equipment manufacturers already displayed self-contained stand alone process tools that are fore-runners of larger tool integration yet to come. Drytek (General Signal) and Applied Materials Technology market dry etch and Chemical Vapor Deposition (CVD) equipment, respectively, that are single-wafer-at-a-time tools with multiple process chambers and thus multiprocess capability. Also MTI-Sypher has now marketed a unit with combined deposition (2 stations) and etching (1 station). The wafers are fed by robots and these tools suggest tool architectures for the further evolution of integrated processes.

Factories of the future will have facilities architecture where cells are linked together. If the operations needed to make an entire integrated circuit are combined under the envelope of one unit tool, then we ultimately have a self-contained factory. If the wafers are transported by automation and robotic manipulation, controlled by a computer, we have a self-contained-automatic-robotic-factory (SCARF)[21]. Many large companies have embarked on similar paths. IBM [22] and Texas Instruments [23] have similar programs.

SCARF System Description

The SCARF project was initiated at the CRSM in mid 1987. We are essentially placing the clean room inside a relatively small envelope, evacuating that envelope, maintaining low particle densities and controlling pressure to quickly allow transfer and load locking between wafer storage areas and process chambers. A specific implementation has been designed, as shown in Figures 3 and 4. A large number of IC fabrication processes are currently being performed in vacuum. The

SCARF design integrates small footprint vacuum tools together around the central chamber. It is convenient to bring certain process tools together locally, especially those which will be used serially in the process architecture.

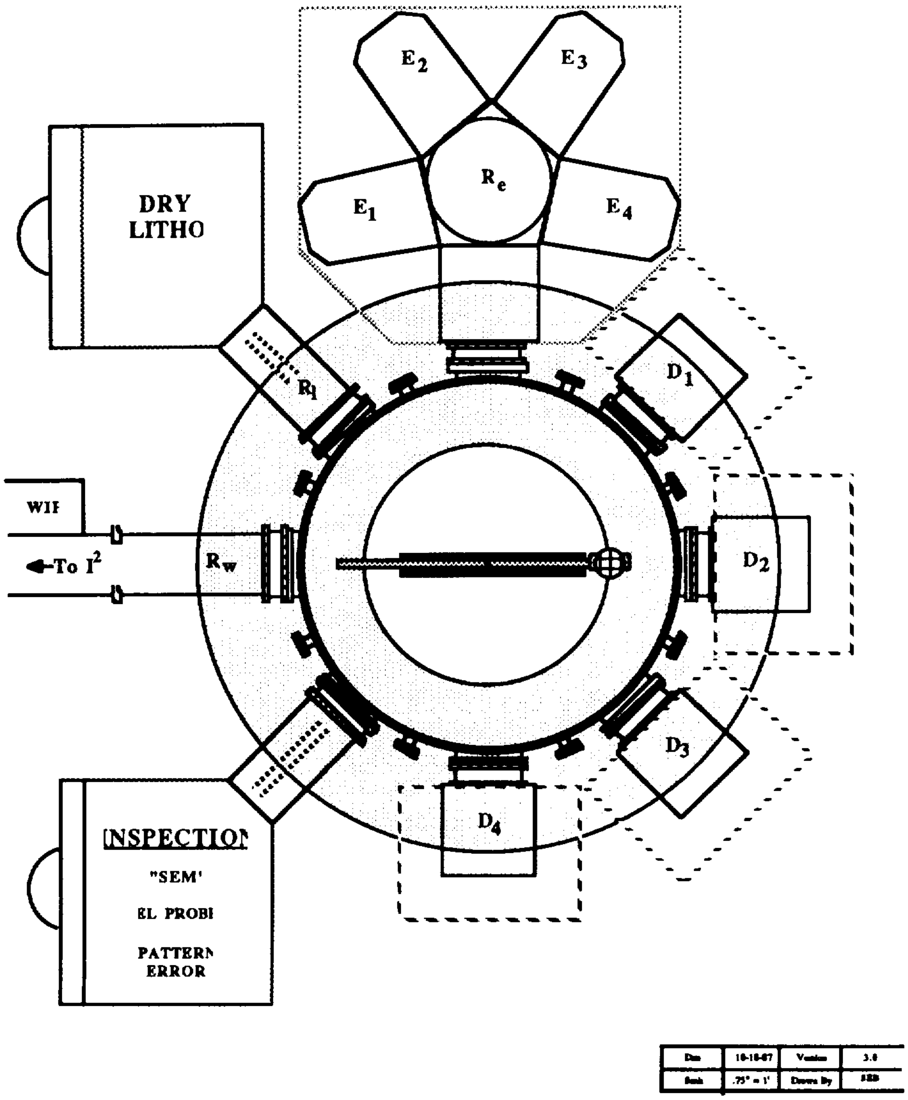

Figure 3. Self-Contained-Automated-Robotic-Factory Layout.
The four deposition chambers in the SCARF are dedicated to a specific process or at least dedicated to a compatible class of chemicals. The central vacuum system has a pumping system that allows base pressures of 10^{-6} Torr. Both rough and controlled limited pumping as well as rough and controlled venting are required for the system. It is important to be able to equalize the pressure between low pressure process chambers and the central vacuum chamber in order to avoid particle transport between chambers.

The chamber is now completed and testing is progressing. The operational parameters of the SCARF facility dictated the design of the central vacuum chamber. The chamber is 50 inches in diameter to provide room for several processing tools around its circumference. There are eight ports around the circumference of the chamber to attach wafer processing equipment. Seven view ports, four on the top and three on the bottom, provide for *in situ* inspections. A 24 inch diameter port on the bottom of the chamber allows quick access to the robot used for wafer transportation.

The entire lid of the chamber is removable to provide greater access to the interior of the chamber. Eighteen small Conflat ports allow electrical and mechanical feedthroughs to be quickly attached to the chamber. The mechanical design of the central vacuum chamber provides the flexibility required in a research environment.

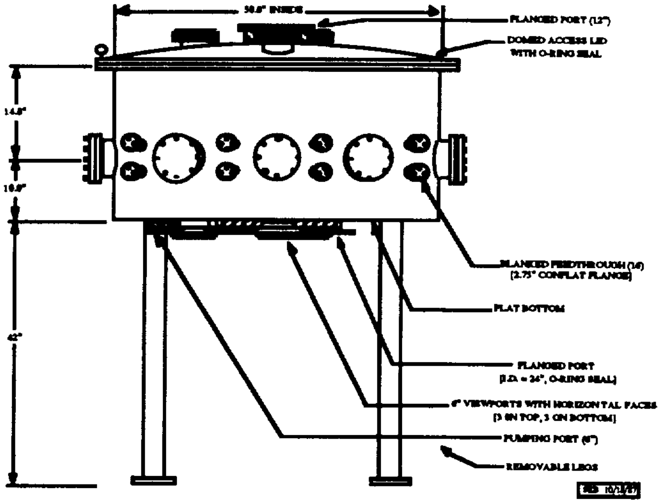

Figure 4. Cross Section of SCARF Chamber

SCARF System Integration
The SCARF system falls under the control of a central host, presently a SUN 3/110 workstation. The SCARF Host Controller is responsible for control and monitoring of the SCARF Chamber functions: pumpdown and vent cycles and rates, gate valve and load-lock sequencing, and acquisition of data from pressure gauges. The next level of control involves the SCARF Robot and the in-vacuum particulate monitor. The SCARF Host Controller can act as a terminal for the SCARF Robot Controller during program development, and will communicate with the SCARF Robot Controller during the test phase and actual process runs. In addition, the SCARF Host Controller will be responsible for data analysis and acquisition. It will serve as the loop control when clean load-locking, transfers and processing steps are accomplished using information fed back from in-situ particle detection. Control over in-vacuum vision inspection tasks is also planned.

Intelligent Operation
Self-contained manufacturing environments are generally characterized in having: a) reduced accessibility and visibility in a crowded workspace making operation by an external operator difficult; b) even when the visibility is possible, access is often costly as it requires exposing the internal environment to atmosphere; c) the work environment is often hazardous. These characteristics require the system to depend on sensors to achieve higher autonomy. The operations must also have a robustness to process variation. Operations such as robot motion within this environment therefore require the development of algorithms for automatic planning of motion so that smoothness can be achieved (to avoid particle generation) and so that obstacles can be avoided[7]. The smooth collision-free trajectory control is required for many mechanisms.

3.2 SENSORS IN VACUUM

VISION
In-Vacuum Color Vision Inspection

As more processes are integrated into a vacuum environment manufacturing system, in-situ inspection will also be required. By performing the inspections in the same vacuum station rather than transferring the wafers to a standard inspection station in clean room, the chance of fatal contamination can be dramatically reduced. Color vision has high potential for process monitoring, metrology and control in IC manufacturing. The increased complexity and decreased lateral and vertical dimensions of semiconductor circuits necessitates accurate, reliable process monitoring. Computer vision, i.e. automated optical inspection, is an important component of automated process inspection and monitoring [24]. Recently, we have designed and built a color vision workstation suitable for automated inspection of integrated circuits [25]. The workstation can readily identify defects that could not be distinguished by black and white processing, even by using gray scale imaging [26]. Furthermore, semiconductor fabrication is in large part a thin film technology. Not only are some materials intrinsically colored, but optical interference effects of semi-transparent layers give films a color characteristic of the film thicknesses.

Color vision can therefore be used in inspection for isolating defects not normally visible in black and white processing. In addition, we have used the relationship between film thickness and color to show the feasibility of a system that can rapidly (~100 milliseconds) measure thin film thicknesses to approximately 20Å accuracy [27]. This can be done by use of a color matching scheme or by incorporating analytical relationships that allows identification of samples of unknown oxide thickness.

Robot Positioning via End-Point Detection in Vacuum
As totally enclosed vacuum processing systems for microelectronics become more advanced, the repeatability with which wafers can be placed for processing becomes a more critical issue. Currently, robots of various sizes and configurations are being used as transfer mechanisms to move wafers between processing stations, with repeatability of placement determined by either motor-mounted encoders or stepper motor drive systems. However, the usual uncertainty of placement position is accentuated greatly in a vacuum chamber, due to the slightly changing shape of the chamber and movement of target areas with respect to each other and the robot over time. To overcome this, it is necessary to implement an end-point feedback system for wafer positioning in the process or inspection chamber.

3.3 IN-VACUUM CLEANLINESS AND PARTICULATE CHARACTERIZATION MEASUREMENT TECHNIQUES

Understanding particle behavior and contamination control in vacuum interface technology is critical to the progress of vacuum-based processes[28]. The dynamic measurement of particles generated during a vacuum operation has to date been difficult to accomplish. The recently developed PM-100 particle monitor made by High Yield Technology is a new type of particle counter and is presently the only one that can be used under vacuum[29]. The system includes a sensor head, a preamplifier, and a controller, and has some unique features. This unit measures particle flux through a light net, which gives information on particle motion as well as the number of particles flowing through during a certain time interval so that real-time monitoring is easily achieved. Sensors such as this are key to monitoring particulate counts in self-contained manufacturing processes.

The probabilistic behavior of this sensor have been studied[30]. The measuring mechanism can be modeled by a Poisson stochastic process with the particle flux to be measured as a parameter of the distribution function. Based on this model, the probability of counting error is estimated. It is shown that when the actual particle flux is significant, the probability of counting error becomes very high. When the product of particle flux and sampling time is small, this probability is approximately a second order function of the sampling time. This sensor, while very useful, gives an intrinsic error in the total particle count. A Bernoulli experiment model can be set up and the formula for recovering the actual total particle count derived.

The cleanliness characteristics of the vacuum environment has been investigated through the use of load-lock chambers and vacuum-compatible particle monitors[31]. It has been demonstrated that most particles will occur at the beginning stage of the rough pumping when the air flow is the maximum and turbulence is expected. The particle count has been related to the turbulence through the time dependent instantaneous Reynolds number. Experimental results indicate a strong relationship between particle count and Reynolds number.

An unexpectedly large number of particles are counted at the rough pumping stage when the chamber is backfilled with clean room ambient air. A nucleation hypothesis proposes that during pumping, the moisture in the air will tend to condense onto fines, and the presence of turbulence will trigger and enhance the condensation process, causing the fines to quickly grow into particles of supermicron sizes[32]. Backfilling with dry nitrogen has led to a dramatic reduction in particle count, although before pumping nitrogen has a very similar particle distribution to that of the clean room air.

In summary, this work characterizes the cleanliness level of vacuum and uses real-time particulate information to minimize contamination levels. Results indicate that vacuum, once achieved (to 10^{-3} Torr and higher) is clearly superior to clean room technology. In general, since there is no air to support particle flow, only newly generated particles will be detected.

4. Conclusion

The problems of clean, contamination free vacuum environments, where complex processes are performed, monitored and verified without human intervention, are not limited to space applications. The microelectronics industry, materials processing, biotechnology and pharmaceutic manufacturing are all tending towards the same direction. In order to produce these new technologies, new manufacturing strategies have to be sought. In particular, the concept of modular, self contained intelligent manufacturing systems offers the possibility of coping with complex processing tasks with high reliability. As many of these manufacturing processes are carried out under vacuum, the design and development of computer controlled mechanisms for manipulating, testing and sensing in this environment become necessary. Vacuum mechatronics is a rapidly developing field of research aimed at solving some of the problems.

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