Autonomous On-Wafer Sensors for Process Modeling, Diagnosis, and Control

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***Abstract*—This paper explores the feasibility of constructing an autonomous sensor array on a standard silicon wafer. Such a sensor-wafer would include integrated electronics, power, and communications, and would be capable of being placed into a standard production process step, or short sequence of steps. During the processing of the sensor-wafer, various process parameters would be measured and recorded. There are several uses for such a sensor wafer, including equipment characterization and design, process calibration, and equipment qualification and diagnosis. In this paper, various sensor architectures, power supplies, communications methods, and isolation techniques are discussed, and particular choices are made. Several proof-of-concept designs that measure film-thickness and temperature are discussed, and test results are reviewed for each design.**

***Index Terms*—Control, calibration, *in situ*, monitoring, real-time, sensor.**

I. INTRODUCTION

OVER the past few years, the semiconductor processing industry has undergone a paradigm shift from *ex situ* metrology to in-line metrology. Wafer measurement equipment has been moved, where possible, from stand-alone measurement stations to integrated measurement systems on or near the processing equipment. The benefits of this shift have been significant. Among the advantages of in line metrology are improved process monitoring, reduced product variance, and higher throughput. By placing the sensors on the equipment, *every* wafer may be examined, as opposed to just a fraction, as is the case with standalone metrology stations. Because more data is available, process fluctuations and trends can be better monitored and recorded. Also, because the data is taken more frequently, adjustments to the process can be made more frequently, so product variance can be reduced. Finally, by measuring all of the wafers in-line and allowing them to continue instead of removing selected wafers for metrology, more production wafers can reach process completion, improving throughput.

While the benefits of in-line metrology are numerous, the money and time spent to integrate metrology stations onto equipment is not insignificant. In addition, equipment engineers are reluctant to modify existing equipment designs to allow the addition of sensors and associated hardware, because such changes could affect process stability and this work is expensive. Also, if the metrology portion of the equipment goes down during production, the equipment must also be taken down to allow repairs to be performed, reducing the throughput of the machine. For these reasons, the next paradigm shift might be from sensors on the *equipment* to sensors on the *wafer*.

Such on-wafer sensors could provide the same information about the wafer and process state as is currently available through equipment-based *in situ* sensors, but without the added cost and complexity of integrating the sensor onto the equipment. Such a wireless sensor-wafer could be loaded into a boat along with product wafers and sent into the processing chamber. Then, as the sensor-wafer is processed, it would either transmit out (via RF, IR, or other wireless method) or record in on-board memory the measurement data. In this fashion the same process information is gleaned, but with minimal invasion into the process chamber.

In this paper, the feasibility of such an on-wafer, spatially-resolved sensor is investigated. A background is then given for the basic features and options that such a sensor could have. Finally, the design, fabrication and testing of several sensor test designs are discussed.

A. On-Wafer Sensor Applications

Spatially resolved *in situ* sensor-wafers would have many important applications in the semiconductor processing industry. These include:

1) Process Characterization/Design: One of the more obvious applications is spatial uniformity characterization during design and development of process equipment. The current equipment development procedure involves processing a set of dummy wafers, measuring the finished wafer parameters, adjusting the machine parameters (chamber geometries, etc.), and then repeating the process. Because this process is typically repeated many times, and each iteration can take a number of days, the entire process can take several months. The reason that such a lengthy procedure is required is that with post-process measurement, only an integrated effect is measured. With a real-time measurement scheme, far fewer

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iterations could be performed because much more information is conveyed during each iteration.

2) Process Calibration: A similar application for *in situ* sensors is process parameter adjustment. Traditionally, dummy wafers are put into the production flow every so often, and measurements from these processed wafers are used to monitor and adjust the process. Typically, about 18% of the production capacity is wasted on process characterization [1]. An alternative to this procedure that is offered by *in situ* sensors is real-time control. By placing an autonomous sensor into the process chamber and closing a real-time control-loop around the tool, process parameters can be optimized automatically, in one step. By using this method, far fewer test wafers would be needed, thereby improving the throughput of the equipment.

3) Equipment Diagnosis and Re-Qualification: Another use for *in situ* sensors is for equipment diagnosis and re-qualification. If a tool in a fabrication facility is malfunctioning, the repair staff needs a quick method of determining the source of the problem, without lengthy disassembly procedures. Typically, the diagnosis of an equipment problem takes several hours. Sometimes, this involves venting and disassembling the process chamber to place wired sensors on the wafer-chuck. By instead using an *in situ* sensor, possible sources of the problem can be eliminated or confirmed more rapidly than by using this disassembly procedure. In a typical fabrication facility machine downtime accounts for 10% of the total equipment time [2]. By reducing this downtime, substantial improvements in throughput can be realized.

In addition, once a machine has been repaired, it needs to be re-qualified for return to production flow. This is typically done by running a minimally processed wafer through the chamber, and by measuring the results. The measurement process is time-consuming, because the metrology equipment in a fabrication facility is highly utilized. By using an *in situ* sensor, the necessary process parameters can be sensed and displayed immediately, eliminating the lengthy metrology delays, and speeding the equipment's return to service.

4) Difficult Measurements: Some measurands are difficult or destructive to measure using current techniques. A few examples of this type of variable are etched sidewall profile and lithographic latent image. Because of the nature of these sensor wafers, they offer the opportunity to measure some of these quantities *in situ*. This would greatly increase the ability of the engineer to evaluate the process.

B. Organization

This paper is organized as follows. First, a general discussion of sensor arrays is undertaken: general requirements, associated difficulties, and possible solutions are discussed. Next, several prototype sensor-wafer designs are presented, and test results from each are reported. Finally, a summary of the ideas presented and the results obtained is provided.

II. DESIGN ISSUES

In developing an autonomous sensor wafer, several important issues must be considered. These issues can be grouped into three main categories: power, communications, and isolation.

A. Power

An *in situ* sensor wafer must contain some type of wireless, regulated power source to provide power for the electronics and sensors. There are several constraints on such a power source. First, to avoid problems with wafer-handling robotics, the protrusion of the power source above the wafer surface must be limited to about 3 mm. Another requirement for the power source is that it does not take up excessive area on the wafer. The smaller the power source, the more space is available for sensors. Lastly, the power source must be capable of supplying roughly 5-V output, with a minimum of 1-mA current, for at least 5 min. This is approximately the amount of power required to keep electronics and sensors running for the duration of a typical process (including loading and unloading).

Given these constraints, several power-supply opportunities exist. The most appealing candidate is battery-power. A range of thin, high-energy batteries exist, ranging from commercial 1-mm-thick watch batteries capable of 25 milliamp hours (mAh), to research-grade 10-μm-thick thin-film batteries capable of 100 microamp hours (μAh) [3]–[10]. In between these ranges lie a number of candidates for on-board power.

Another possibility for a power source is the photovoltaic cell. In several processes, plasma is used. Because the plasma emits intense visible light at a range of wavelengths, this light could be used as a power source. Using photovoltaic cells with a 15% efficiency [11], a cell area of 1 cm^2, and 1 mW/cm^2 of available broadband light power inside a typical plasma chamber [12], the available electrical power is:

$$P_{\text{avail}} = 15\% \times 1 \frac{\text{mW}}{\text{cm}^2} \times 1\ \text{cm}^2 = 150\ \mu\text{W}. \tag{1}$$

In nonplasma processes, or where this power level is too low, an external laser could be focused on the photovoltaic cell to provide power from outside the chamber. Using this method, as much as 5 mW could be generated using a similar area [13].

Other, more exotic power sources exist, such as using a large capacitor to store energy for the sensor. In such a scenario, the capacitor would be charged up by an external power source prior to being placed into the processing equipment. Then, while the sensor is being processed, the capacitor would be discharged to provide power for the sensor. The main problem with this idea is that, for the typical energy levels needed by the sensor, the capacitor would have to be much too large. For example, using typical capacitor materials and dimensions, to maintain a current of 1 mA at a voltage above 3.5 V for 5 minutes, the capacitor would have to be 6.7 m^2 in area [13], which is clearly much larger than a wafer. Even using novel capacitive structures to reduce the area, very large areas would still be required. One final power source option is the direct utilization of the RF energy present in plasma discharge processes. By inductively coupling to the RF biases present across the plasma sheath, large amounts of power can be extracted. The most difficult aspect of such a power source is the coupling and regulation of RF energy.

B. Communication

For an *in situ* sensor wafer to be useful, the data it measures must be communicated to the outside world. Therefore, several restrictions exist for the sensor's communication system. First, typical semiconductor process variations, such as those occurring in plasma etch, CVD, and lithography, occur across length scales of several centimeters and time scales of several seconds. Therefore, the system must be capable of handling measurements from about 100 sensors (to get the desired spatial resolution of 1 sensor per ≈ 4 cm^2), each operating at a minimum frequency of about 1 Hz. Second, the communications system must allow measurements with reasonably high dynamic range to be transmitted, at least 8 bits per measurement. Therefore, the overall communications bandwidth must be at least (100 sensors)*(1 Hz)*(8 bits) $= 800$ bps. Another requirement for the communications system is that it uses very little power. Because the power source is only capable of delivering a limited amount of power and energy, the communications system must use only a fraction of these amounts. For the same reasons as for the power supply, the communications system must be wireless, and must fit within the same size constraints. Lastly, the communication system must not, as much as possible, depend on the particular geometry of the process-chamber. For example, if optical communications is used, the light-source must not be directed only toward the view port in a particular type of equipment, because then this sensor would be useless in other chambers in which the viewport is situated differently with respect to the wafer chuck. Alternatively, a directional communications system should be easily reconfigurable to work with multiple chamber geometries.

For a multisensor wafer the communications can be either modular or central. For modular communication, each sensor (or possibly each group of sensors) would have its own communication system, so that separate sensors or groups of sensors transmit their data in parallel. With central communications, all of the sensors on a wafer are connected to a central communications system, which communicates the data for the entire wafer. In this way, there would be a single transponder on each wafer that multiplexes the measurement values, and transmits them serially. At the receiving end, the receiver demultiplexes the information to yield sensor information from all points on the wafer. Typically, the type of communication system (LED, RF, etc.) will determine whether modular or central communications will be used. This will be discussed in more detail below.

Perhaps the easiest communications option is optical transmission. With this method, a light-emitting diode (LED) on the wafer transmits the sensor data to a photosensitive receiver outside the chamber using some type of frequency-modulation scheme. Plenty of low-profile, low-power commercial components currently exist that could provide this type of functionality. This method has the disadvantage that a line-of-sight path to the wafer is required. In many cases, such a view port exists, but in several types of processing equipment this is not possible. This technique can be used with either modular or central communications, but because LED power requirements are relatively high, and modular communications would require many LEDs on the wafer, this method is less advantageous. Therefore, for an optical scheme, centralized communications would most likely be employed.

Using radio-frequency (RF) communication is also an option. By placing an RF oscillator and modulation circuitry on the wafer, sensor data can be transmitted out of the chamber to external receiver circuitry. Commercial components also exist that provide RF communication capability, although they use more energy than their optical counterparts. This has the advantage that it does not depend on chamber geometry (placement of viewports, etc.) as much as optical transmission. However, for plasma processes the plasma itself forms a conductive cloud around the wafer, impeding RF transmission. Another downside to using RF is the complexity of RF transmission circuits and their high power requirements. Because of these requirements, centralized communications techniques would be used for RF.

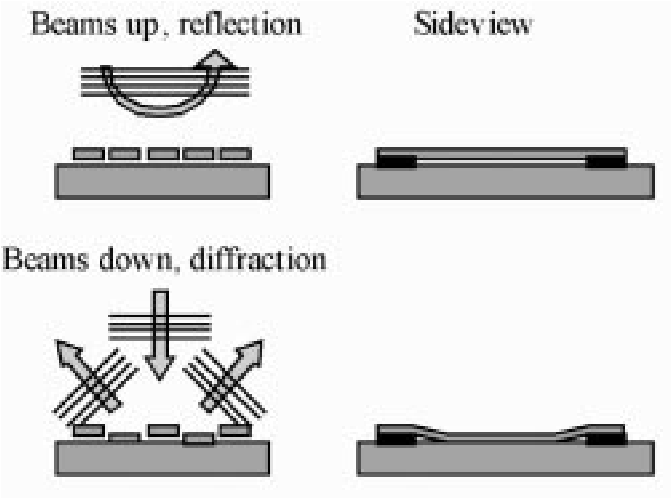

Fig. 1. MEMS grating light modulator diagram.

A third possible communication system is the so-called grating light modulator (GLM) [14], [15]. This microelectromechanical system (MEMS) consists of a microfabricated set of refractive beams, placed as shown in Fig. 1. In the unactuated state, shown on the top of Fig. 1, light that strikes the surface will be completely reflected, because the surface is flat. However, when the modulator is actuated, shown on the bottom of Fig. 1, every other beam is electrostatically pulled down to the substrate, creating a diffraction grating. In this way, information can be modulated onto an incoming beam of light. An SEM photograph of this structure is shown in Fig. 2. The major advantage of this method of communication is that it requires very little power. Since the only power required is that needed to electrostatically move the bottom plate, which typically weighs about 2×10^{-10} kg, *extremely* low power levels are needed. Because GLMs require such low power and can be interrogated by a directed laser beam, modular communications techniques would probably be used. One retroreflector could be placed next to each sensor, and the scanning laser would read the data from the sensor nearest the laser spot. However, this method requires a directed line-of-sight view of the wafer so that a laser can be focused on the retroreflector. As with optical communications, this makes the design very equipment-dependent.

C. Isolation

Because most of the processing techniques used in the semiconductor manufacturing industry place the wafers in "harsh"

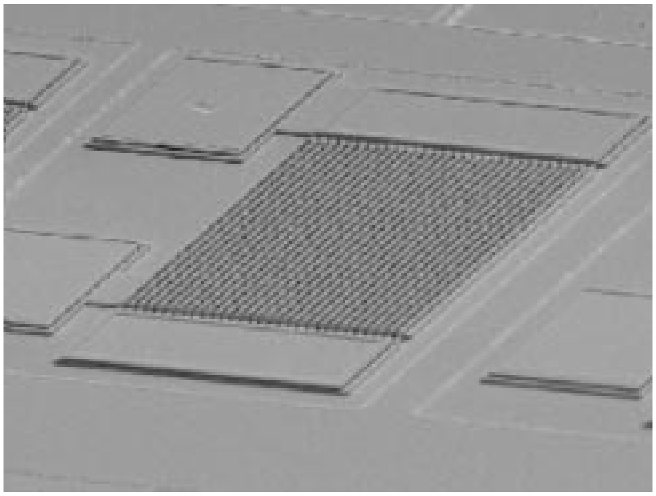

Fig. 2. MEMS grating light modulator SEM photograph.

environments, any sensor that will be processed by the equipment needs to have some type of isolation from the environment. The main conditions that would be detrimental to a sensor wafer are high temperature and electrical noise. Also of importance are chemical attack and physical damage (such as etch damage).

In rapid thermal processing (RTP), for example, the temperature typically exceeds 1000 °C. Any electronics on the wafer that are not isolated will stop functioning above about 150 °C, and will physically melt above 660 °C (the aluminum interconnect melting temperature). Therefore, any sensor wafer that might operate in this environment *must* be thermally shielded so that the electronics remain at a lower temperature.

In plasma environments, the plasma is typically created by coupling radio-frequency (RF) power into a gas. Because of this high-power RF energy, surface currents are generated in exposed, unshielded conductors on the wafer surface. Therefore, if electronics are functioning on the wafer (as in the case of a sensor-wafer), then these generated currents might interfere. So a sensor wafer taking measurements inside a plasma chamber must be electrically isolated from the plasma environment to function properly.

One possible option to isolate the electronics and sensors from electrical noise is to add a metal layer over all of the electronics (but isolated by an oxide), and have a contact from this overcoat to the substrate. In this way, the top metal layer would shield the electronics below by providing a ground path. The main method for offering shielding from chemical and physical attack is through the use of some type of overcoat. By covering the electronics, and possibly the sensors, with an oxide layer, for example, most chemical and physical processes would only attack the oxide and not the underlying electronics. When used in conjunction with the metal layer described above, this method provides isolation from electronic, chemical, and physical problems. To isolate electronics from high temperatures, more complex measures need to be taken. One method for providing this isolation is to create a microfabricated “vacuum chamber” around the electronics, so that thermal conduction and convection are virtually eliminated [17]. Then, by adding appropriate coatings to the walls of the chamber, radiation heat transfer can be minimized. The process to achieve an evacuated chamber around electronics is somewhat complex, but Klaassen [18] has successfully fabricated thermally isolated RMS power sensors for RF applications.

III. EXPERIMENTAL RESULTS

We have designed and fabricated several sensor wafers to assess the viability of our ideas. To better organize this research, the project was divided into two halves. One half investigates the power, communication, and isolation issues, and the other half researches novel sensor structures. In this way, the project complexity can be reduced to a manageable level. For example, in researching sensors, wired power and communications are utilized to eliminate those concerns.

A. Power, Communications, and Isolation

One of the intended uses for this type of sensor is the development of next generation processing equipment, which typically uses larger wafers than the currently available technology. Therefore, if the sensor wafers are to be fully fabricated using an available process, large sensor wafers cannot be made because the processes needed to do so are still in development. If, instead, only one or two low-resolution metal lines are patterned onto the wafer (the “base wafer”), and these lines serve to interconnect electronic modules that are mounted to the surface of the wafer, then the wafer will be much less expensive, and more feasible to construct. This is the technique we have chosen to use for our power, communications, and isolation test bed (the “component-based” wafer).

Our first component-based wafers have been temperature-sensor wafers, for use on both bakeplates and in plasma-etch equipment. In the post-exposure bake (PEB) process for deep-ultraviolet (DUV) lithography, the thermal transients that the wafer experiences when it is dropped onto and removed from the bakeplate are critical to the accurate reproduction of features on the wafer [19]. Currently, there is no accurate method for measuring these transients, since the sensors must be wireless to accurately reflect the transients experienced by the wafer during robotic handling. In the plasma-etching process, thermal gradients across the wafer are critical to the etch uniformity [20]. The chemical nature of the etch-process makes it extremely sensitive to temperature as modeled by Arhennius relationships. Therefore, accurate spatially and temporally resolved thermal measurements are essential to characterizing and controlling spatial etch nonuniformity.

1) Temperature Sensor—Design I: For this design, we decided to employ a battery-based power source, optically based communications, and no isolation. This design was targeted for use on a bakeplate up to 150 °C. For this reason, no physical or electrical isolation is necessary, and only thermal protection needs to be considered.

The first prototype wafer we built involves a simple resistance-to-frequency conversion circuit. A 555 timer chip is used to generate a pulse train input to a visible LED, and the frequency of the pulse train is determined by the resistance of a thermistor mounted on the wafer. In this way, the external flash-frequency can be used to deduce the wafer temperature.

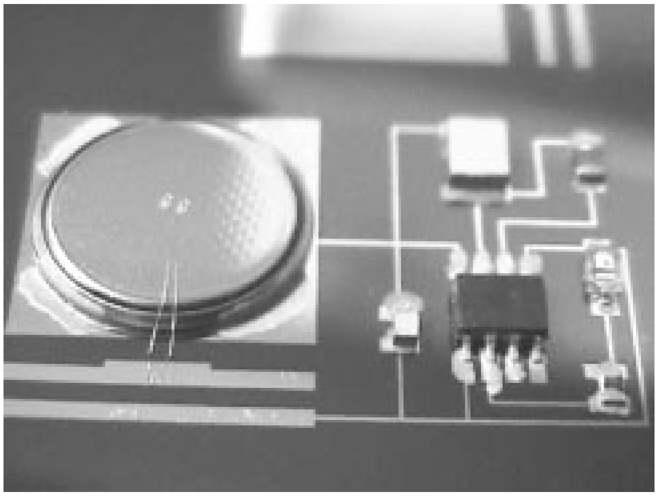

Fig. 3. First temperature-sensor wafer design.

An alkaline watch-cell battery provides the power source for this wafer. A photo of this design is shown in Fig. 3.

The temperature data from this particular sensor wafer was not very accurate (within 5 °C). It was adequate, however, to demonstrate the viability of battery-based power sources and optical communications. Due to the amount of visible light interference, it was decided that modulated infrared (Ir) communications were necessary for subsequent designs.

2) Temperature Sensor—Design II: The next design moved to a microprocessor-based scheme. Instead of directly modulating the information to the LED, a microprocessor with an integrated 8-bit analog-to-digital (A/D) converter is used to manipulate the data. It then uses a standard IrDA communications protocol to transmit four bytes of temperature data (one byte per sensor) and 23 bytes of IrDA overhead at 9600 baud to an external detector. It makes two such transmissions per second. The IrDA protocol is compatible with the PalmPilot[1], which allowed us to write an application to directly display the data in real time. Again, thermistors are used as temperature sensors, and the temperature readings from this sensor wafer are more accurate (within 3 °C). All of the components are mounted to the wafer using silver paint, which is a liquid paint that becomes electrically conductive when it dries. The silver paint was used because ordinary solder does not adhere to the aluminum interconnections on the wafer. This design is shown in Fig. 4.

Because of the impedance requirements of the A/D converter, this design required an external amplifier to match the thermistor impedance to the A/D converter input impedance. Also, because of the thermal characteristics of the thermistors used, the usable temperature range of the sensor system was limited. For these reasons, we wanted to use a different type of temperature sensor in subsequent designs. For convenience, we also wanted to use a rechargable battery.

3) Temperature Sensor—Design III: The last temperature-sensor wafer we designed improved on our second design in several respects. This wafer uses a voltage regulator chip to maintain constant supply voltage, and two lithium rechargable batteries to extend its working life. The wafer uses temperature sensor modules, which are surface-mounted chips that output a voltage proportional to temperature. In this way, the analog amplifier can be removed, and the sensor outputs can be fed directly into the 8-bit A/D converter. On this wafer, the metal layer consists of an aluminum-nickel sandwich. Because solder adheres to nickel, the electrical connections were made by placing solder paste on the pins and dropping the wafer onto a heated bakeplate for 1 minute. In this way, all connections were made in parallel, and they are much more mechanically and electrically reliable than the silver paint connections used previously. This design is shown in Fig. 5.

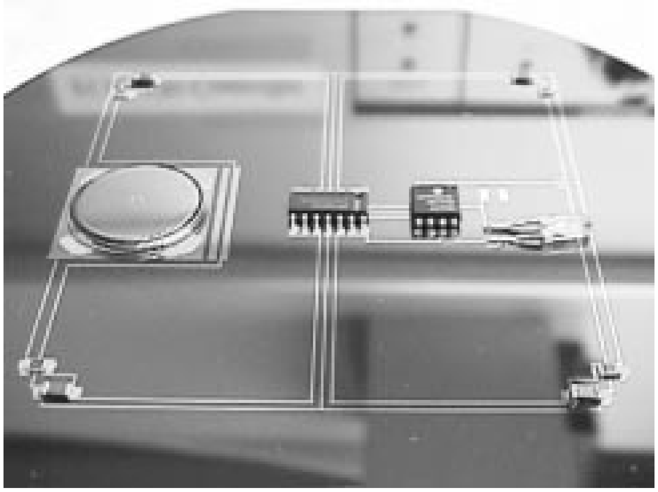

Fig. 4. Second temperature-sensor wafer design.

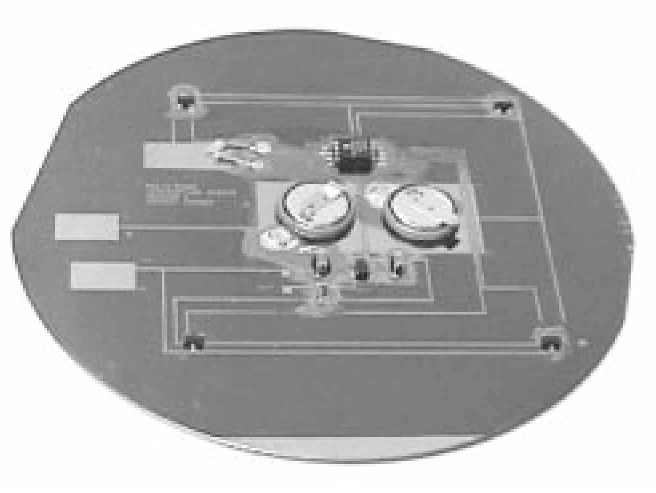

Fig. 5. Third temperature-sensor wafer design.

This wafer is able to last about 11 h on a full battery charge, and is able to give accurate temperature readings (within 1 °C) up to 120 °C. The temperature-limiting components of the wafer are the batteries, and by removing these and using external power, temperatures up to 150 °C can be measured. A sample of this data for a multiple temperature cycle experiment is shown in Fig. 6. It is evident from this figure that the sensor tracks the temperature recorded by the bakeplate instrumentation well, is able to function up to at least 120 °C, and survives multiple temperature cycles with no adverse effects. To examine the transient response of the sensor wafer, it

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[1] PalmPilot is a trademark of the Palm, Inc.

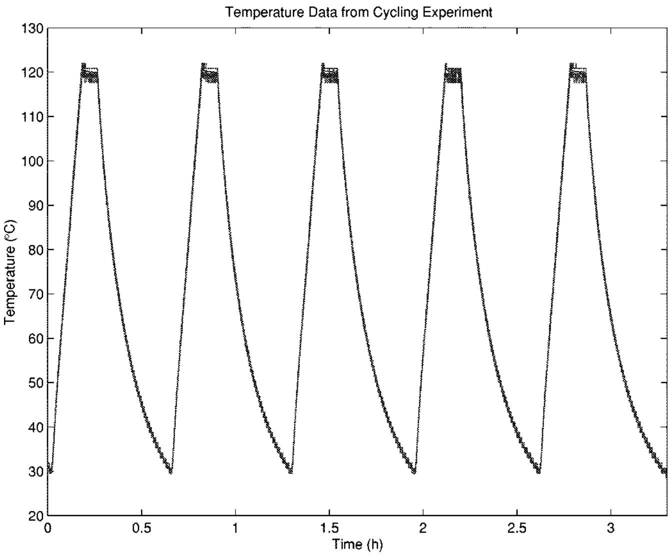

Fig. 6. Temperature cycling experiment using third temperature-sensor wafer design. Five plots are shown: four sensor outputs, and the actual bakeplate temperature.

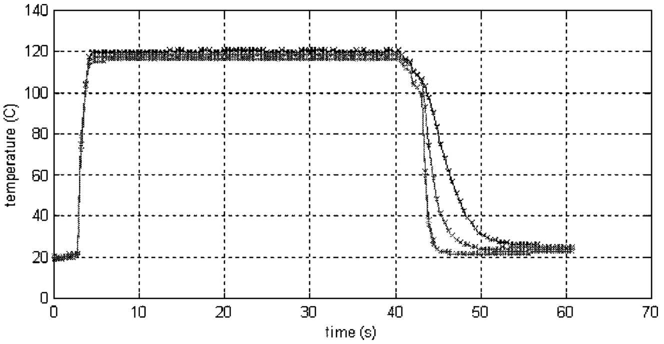

Fig. 7. Temperature measurements during a run through a SVG developer track. The temperature given by four sensors are shown.

was run through a photoresist developer track (SVG-8132CTD Positive Photoresist Development System), with a temperature controlled 120 °C bakeplate and a 25 °C chill plate. The results of this experiment are shown in Fig. 7. The settling time of the sensors for the heat-up phase was under 2 s, indicating very little thermal sensor lag. While the cool-down phase shows significant deviations in settling time among the sensors, this could be due to the cooling effect of the robotic arm that moves the wafer between plates.

This sensor wafer was then used to measure the temperature at the wafer surface during plasma etching. In order to protect the sensor wafer against the harsh environment in the plasma reactor, the components on the wafer surface were covered with a layer of infrared transparent epoxy. Experiments were conducted in an IPC Barrel Plasma Reactor, which is used for ashing photoresist, and for etching oxide and nitride. It can generate O_2 and SF_6 plasmas with a maximum power output of 300 W. The sensor wafer was subjected to a O_2 plasma at 0.76 Torr with power up to 100 W. The temperature sensor output for a constant RF power of 100 W is shown in Fig. 8. As expected, the temperature at the wafer surface increases slightly over time during the etch. These results prove that properly designed electronics can successfully operate and communicate inside of a plasma.

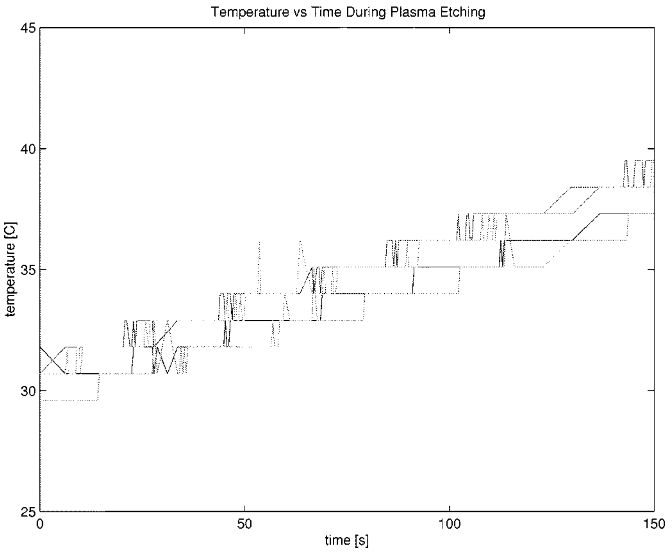

Fig. 8. Temperature measurements during plasma etching in an IPC barrel plasma reactor. The temperature given by four sensors are shown.

B. Sensor Structures

The first sensor structure attempted was a film thickness sensor for the polysilicon plasma etch process. Because plasma etching is used to define the gate structures in CMOS processes, it is a highly sensitive and critical step. The etch uniformity, selectivity, and anisotropy are all closely monitored to ensure that the etch proceeds correctly. Small differences in the etch-rate across the wafer can lead to critical dimension (CD) nonuniformity, which can directly affect circuit performance. A spatially resolved film thickness sensor could be used to design a process with optimal uniformity, to monitor the process, or to diagnose equipment problems.

Our sensors use a van der Pauw sheet resistance measurement scheme to measure the film thickness. Using this method, the resistance of a "slab" of polysilicon is measured. Based on the known resistivity and size of the slab, the thickness can be deduced.

1) Etch Rate Sensor—Design I: The sensor structure used in this design is called a van der Pauw sheet resistance measurement structure (see Fig. 9). In this structure, four electrical probes are placed around the perimeter of an square sheet of material. By injecting a current through two of the probes, and measuring the resulting voltage across the other two probes, the thickness of the sheet can be calculated [21]:

$$t = \frac{\ln(2)\rho}{\pi}\frac{I}{V}. \tag{2}$$

The van der Pauw structure was fabricated on the gate polysilicon layer of the complimentary metal oxide semiconductor (CMOS) process. Metal interconnections were used to connect the corners (the probed points) to the measurement circuitry. The remaining SiO_2 layers were placed over this polysilicon structure, including the overglass layer. Then, once the CMOS process was finished, a 13th masking step followed

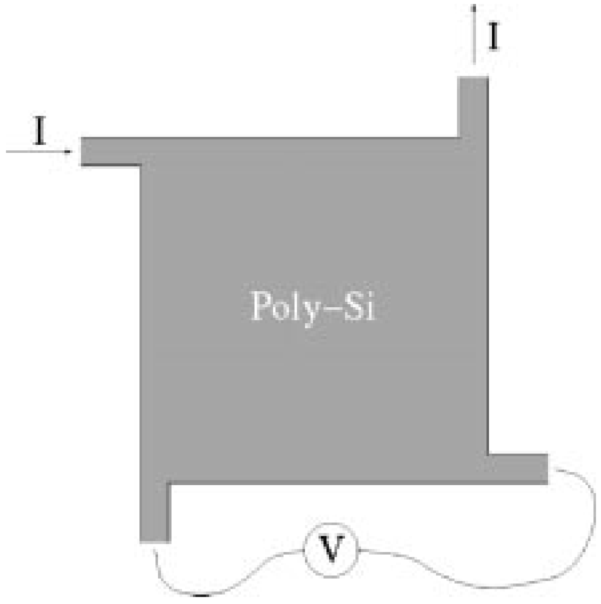

Fig. 9. Diagram of van der Pauw structure operation.

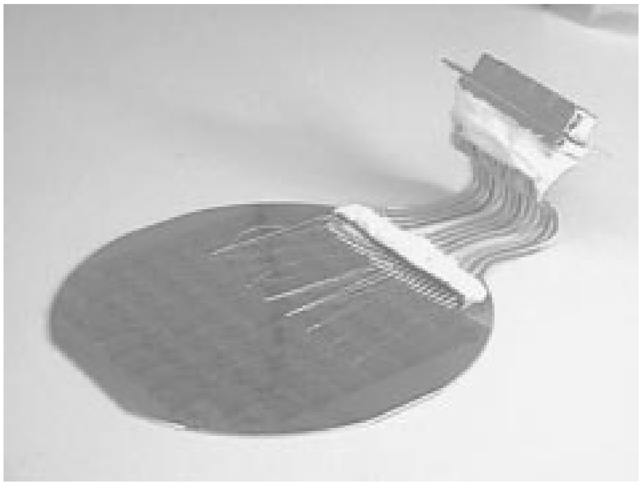

Fig. 10. Picture of sensor wafer with wires attached.

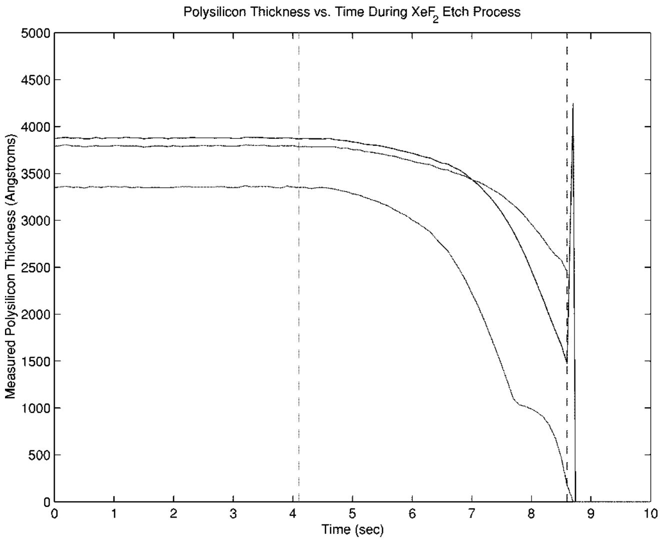

Fig. 11. Data from *in situ* etch experiment. The green line indicates the beginning of the etch process, and the red line indicates the point at which sensor communication was lost.

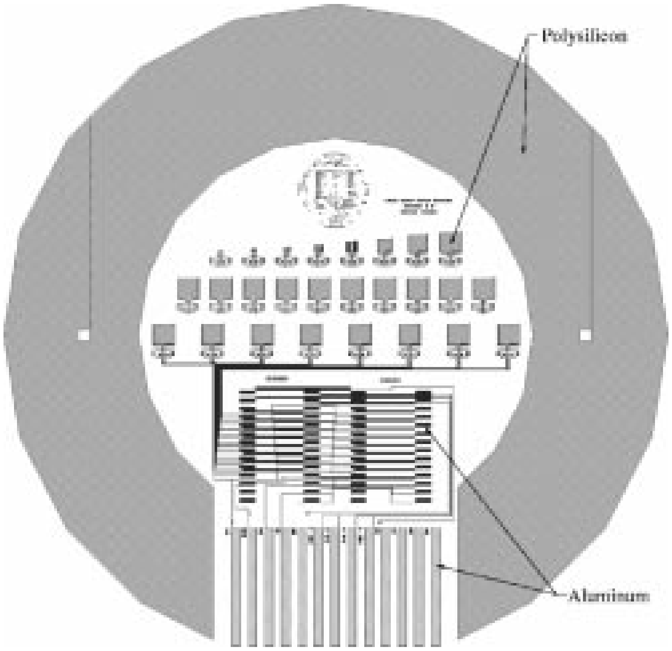

Fig. 12. Layout of the second design.

by a wet SiO_2 etch was used to selectively etch back to the polysilicon sensor surface.

To avoid the problems associated with testing the sensor under plasma conditions, we tested this wafer using XeF_2, an isotropic, nonplasma silicon etchant. Wires were passed into the chamber through the Plexiglas lid, and data was collected from the sensors during the etch.

Because XeF_2 etchant is highly sensitive to loading effects, the polysilicon etch proceeded at a very rapid pace due to the low open area of the sensor structures. Fig. 11 shows the thickness vs. time curves as measured by the sensors during an XeF_2 etch process. As can be seen from the figure, the sensor thicknesses drop from their initial values to near-zero within 6 s. Once the first sensor etches away at $t = 8.6$ s, the signal is lost from the other sensors since all sensors are series-connected; data after this point shows only electrical noise. While these data discernibly indicate the etching of the polysilicon film, no postetch measurement confirmation could be performed. As a result, the accuracy of the sensors could not be calculated. The decision was made to fabricate another test wafer, with features designed to overcome these problems.

2) Etch Rate Sensor—Design II: The next sensor wafer design utilizes the same sensor structure as the previous design (the van der Pauw probe), and its purpose is to eliminate or reduce the problems encountered in the testing phase of the first design. These problems included high etch rate and long design turn-around time.

The first problem, the high etch-rate, was solved in the new design through the use of a "guard-ring" of polysilicon around the edge of the wafer. This extra band of polysilicon serves to increase the open area to around 50% (from 0.13% for the previous design), loading-down the XeF_2 reactor and reducing the etch-rate dramatically. This guard-ring can be seen in Fig. 12.

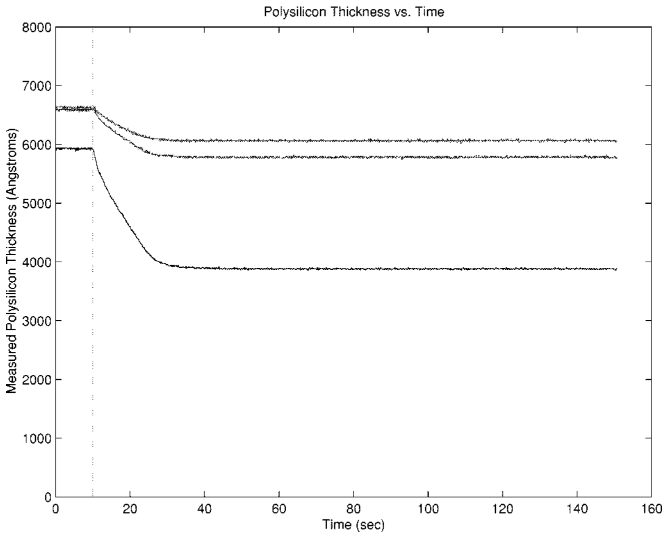

Fig. 13. Sensor-measured film thickness during XeF_2 etch. The green line indicates the beginning of the etch process.

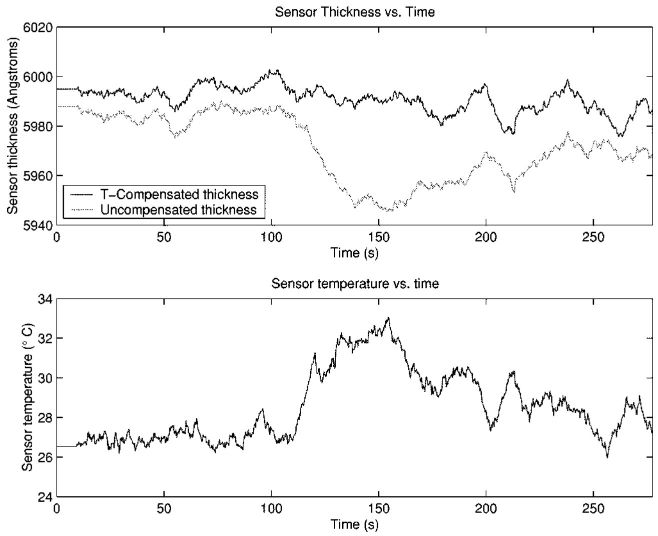

Fig. 14. Sensor-measured film thickness and temperature during a period of constant film thickness. The thickness plot shows both uncompensated and temperature-compensated thickness values.

This wafer used a much more simple process consisting of only two masking layers, to reduce the process turn-around time to about two weeks (from one year for the previous design).

Testing was carried out as described in Section III-B1 and a sample of the recorded data is shown in Fig. 13. At the current and voltage levels used to drive the sensors, each sensor consumed about 100 μW, which is well within the capability of a typical battery power source.

Using the data collected, the accuracy, repeatability, and stability of the sensor were evaluated. The average bias of the sensor was calculated to be ± 3.1 Å, and the maximum observed bias was ± 45.9 Å, which corresponds to a 0.7% error. The repeatability of the sensor during the experiments was found to be ± 13.1 Å, and this is mostly due to electrical line noise from the cables used to transfer signals to the wafer. Over a 15-min period of time, the sensor output drifted by 3.2 Å, which most likely stems from a change in temperature and hence a change in the polysilicon resistivity.

3) Etch Rate Sensor—Design III: With the previous design, it was noticed that the film thickness signal produced by the van der Pauw sensor is sensitive to temperature. Because polysilicon resistivity changes with temperature, there is no way to deconvolve the effects of thickness loss and temperature variation using a single sensor. For this reason, a third design was fabricated which includes a buried van der Pauw structure next to each film thickness sensor. Because this sensor is isolated from the etch environment by an oxide layer, its thickness does not change, and the resistivity variation due to temperature can be measured. Using this signal, the thickness sensor can be compensated for variations in temperature.

Fig. 14 shows a sample data set in which no polysilicon etching took place, but the temperature of the wafer varied. The output of the temperature sensor is shown in the bottom plot, while both the raw and temperature-compensated output of the film thickness sensor are shown in the top plot. As can be seen from the figure, the temperature of the wafer rises sharply at 120 s, and this causes an apparent loss of thickness in the uncompensated sensor. However, the temperature signal can be used to compensate for this temperature fluctuation, as shown by the temperature-compensated trace.

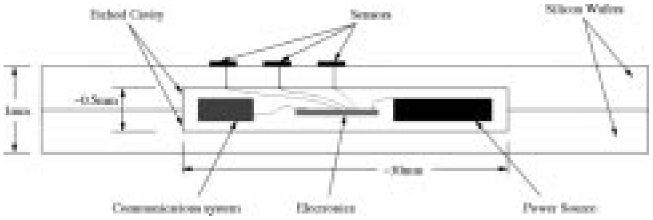

Fig. 15. "Clamshell" sensor wafer structure, with electronics, battery, and communication system enclosed inside a wafer, and only sensors exposed on the surface.

IV. FUTURE VISION

Using the techniques discussed in this paper, it is theoretically possible to create a structure like the one shown in Fig. 15. In this design, the electronics, power source, and communication system are placed into a hollow cavity ($\approx$30 mm on a side, 0.25 mm deep) etched into a silicon wafer. Another wafer with a similar cavity is placed over the top of this, and the two are hermetically bonded together. The sensors are placed on the outside surface of this "clamshell" wafer, and wires are routed through the shell to the inside electronics. In this way, the sensor wafer "looks" very similar to a standard wafer, which means that it will cause very little disruption of the process or handling robotics. Because silicon is transparent to some infrared wavelengths, a communication system using infrared light can be embedded into the wafer, with no protrusion.

One of the main benefits of this system, beyond nonintrusiveness, is its ability to withstand higher temperatures. If the internal cavity is filled with either a high thermal resistivity material or vacuum, then the inside components will be significantly thermally isolated from the exterior. If this resistance is high enough, the sensor wafer can potentially be used for sensing in very high temperature processes, such as RTP, without being damaged.

V. CONCLUSION

We believe the concept of on-wafer *in situ* sensors to hold promise. While we have demonstrated proof-of-concept, a host of design, manufacturing, reliability, and cost issues need to be investigated in order for these sensors to gain widespread acceptance.

In our work, we have demonstrated the operation of a wireless temperature wafer which is capable of reporting wafer temperature at four locations to within 1 °C up to 120 °C. This wafer is able to report its temperature in real time, and can last through a 30 min process. We have also demonstrated a polysilicon film-thickness sensor that is capable of reporting film thickness with an accuracy of better than 50 Å, and a repeatability of under 15 Å. This sensor has been shown to function during an etch process, and requires relatively low power to operate (100 μW). Work is in progress to marry the power and communication scheme from the temperature wafer to the sensing abilities of the sensor wafer, to achieve a wireless film-thickness sensor. Work is also in progress on isolation schemes so that this wafer can be used in a plasma process.

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REFERENCES

[1] *National Technology Roadmap for Semiconductors 1997 Edition*, 1997.
[2] *Int. Technology Roadmap for Semiconductors 1999 Edition*, 1999.
[3] J. B. Bates, "Rechargeable lithium microbatteries," in *5th Int. Symp. on Micro Machine and Human Science Proc.*, Oct. 1994, p. 7.
[4] H. Durakpasa, M. W. Breiter, and B. Dunn, "Impedance studies of sol-gel materials," *Electrochem. Act.*, vol. 38, p. 371, 1993.
[5] B. Dunn, G. C. Farrington, and B. Katz, "Sol-gel approaches for solid electrolytes and electrode materials," *Solid State Ionics*, vol. 70, p. 3, 1994.
[6] F. Chaput, B. Dunn, P. Fuqua, and K. Salloux, "Synthesis and characterization of vanadium oxide aerogels," *Non-Crystalline Solids*, vol. 188, p. 11, 1995.
[7] K. Salloux, F. Chaput, H. P. Wong, B. Dunn, and M. W. Breiter, "Intercalation in vanadium pentoxide aerogels," *J. Electrochem. Soc.*, p. 142, 1995.
[8] B. C. Dave, B. Dunn, F. Leroux, L. F. Nazar, and H. P. Wong, "Vanadium oxide/polypyrrole aerogel nanocomposites," in *Mater. Res. Soc. Symp. Proc.*, vol. 435, 1996, p. 611.
[9] W. Liu, G. C. Farrington, F. Chaput, and B. Dunn, "Synthesis and electrochemical studies of spinel phase $\lim n_2o_4$ cathode materials prepared by the pechini process," *J. Electrochem. Soc.*, vol. 143, p. 879, 1996.
[10] P. W. Wu, S. R. Holm, A. T. Duong, B. Dunn, and R. B. Kaner, "A sol-gel solid electrolyte with high lithium ion conductivity," *Chem. Mater.*, vol. 9, p. 1004, 1997.
[11] L. M. Koschier, S. R. Wenham, and M. A. Green, "Efficiency improvements in thin film silicon solar cells using $\mathrm{Si}_{1-X}\mathrm{Ge}_x$ alloys," in *Proc. 2nd World Conf. and Exhibition on Photovoltaic Solar Energy Conversion*, July 1998.
[12] C. Cismaru, J. L. Shohet, and J. P. McVittie, "Plasma vacuum ultraviolet emission in a high density etcher," presented at the P2ID Conference, Monterey, CA, May 10-11, 1999.
[13] M. Freed, "in situ Etch Rate Sensor Arrays for Plasma Etch Processes," Dept. Mech. Eng., Univ. of California at Berkeley, May 1999.
[14] O. Solgaard, F. S. A. Sandejas, and D. M. Bloom, "A deformable grating optical modulator," *Opt. Let.*, vol. 17, no. 9, pp. 688–690, May 1992.
[15] O. Solgaard, "High-resolution silicon surface micromachined displays," in *Tech. Dig. IEEE/LEOS IEEJ/SAMS 1997 Int. Conf. Optical MEMS and Their Applications*, Nov. 1997, pp. 9–14.
[16] D. S. Gunawan, L. Y. Lin, and K. S. J. Pister, "Micromachined corner cube reflectors as a communication link," *Sens. Actuators A, Phys.*, vol. A47, no. 1–3, pp. 580–583, Mar 1995.
[17] G. T. A. Kovacs, *Micromachined Transducers Sourcebook*. New York: WCB McGraw-Hill, 1998, pp. 586–587.
[18] E. H. Klaassen, "Thermal AC to RMS Converter," Dept. Elect. Eng., Stanford Univ., Stanford, CA, May 1996.
[19] J. Sturtevant, S. Holmes, T. VanKessel, P. Hobbs, J. Shaw, and R. Jackson, "Post-exposure bake as a process-control parameter for chemically-amplified photoresists," *SPIE Integ. Ckt. Metrology, Inspection and Process Control*, vol. 1926, pp. 106–114, 1993.
[20] D. Tretheway and E. S. Aydil, "Modeling of heat transport and wafer heating effects during plasma etching," *J. Electrochem. Soc.*, vol. 143, p. 3674, 1996.
[21] D. K. Schroder, *Semiconductor Material and Device Characterization*. New York: Wiley Interscience, 1990, pp. 1–13.
[22] D. Fisher, M. Freed, C. Spanos, and K. Poolla, "Micro-sensor arrays for calibration, control, and monitoring of semiconductor manufacturing processes," in *Proc. IEEE Int. Conf.Control Applications*, Aug. 1999, pp. 784–788.
[23] ——, "Autonomous micro-sensor arrays for process control of semiconductor manufacturing processes," in *Proc. 38th Conf. Decision and Control*, Dec. 1999, pp. 4179–4184.
[24] M. D. Baker, F. R. Williams, and G. S. May, "A novel *in situ* monitoring technique for reactive ion etching using a surface micromachined sensor," *IEEE Trans. Semiconduct. Manufact.*, vol. 11, pp. 254–265, May 1998.

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