Real Time In-Situ Data Acquisition Using Autonomous On-Wafer Sensor Arrays

Mason Freed, Michiel Krüger, Kameshwar Poolla, and Costas Spanos
BCAM-Group, Univeristy of California at Berkeley, 5105 Etcheverry Hall, Berkeley, CA 94720
Corresponding Author: kruger@jagger.me.berkeley.edu

Abstract – This paper explores the feasibility of integrating in-situ sensors onto the surface of a silicon wafer, with the objective of placing this wafer into a processing tool to obtain real time measurements. This technique has numerous benefits: increased measurement speed, reduced sensor introduction cost, and increased spatial and temporal information. Various sensors and sensor wafers have been developed and tested in a variety of processing tools. Repeatable, real time measurements in harsh environments such as high temperature and plasma have been obtained.

Index Terms – Sensor wafer, autonomous operation, in-situ data acquitsition, wireless communication

INTRODUCTION

In-line metrology in semiconductor manufacturing has numerous advantages such as improved process monitoring, reduced product variance and higher throughput. For this reason, many wafer measurement sensors have been integrated with processing tools. However, the efforts to achieve this integration are not insignificant and problems with the sensors and associated hardware may result in downtime of the processing equipment. An autonomous sensor wafer [1] could provide an alternate method of obtaining the same information about the wafer and the process state, while eliminating the aforementioned problems.

This paper explores the feasibility of integrating in-situ sensors onto the surface of a silicon wafer and placing this wafer into processing tools to obtain real time measurements. This technique has numerous benefits: increased measurement speed, reduced sensor introduction cost, and increased spatial and temporal resolution.

The major challenges to the implementation of on-wafer sensors are isolating them from the processing environment, communicating with them during the process, and providing electrical power to run them for the duration of the process. Of course, all of this must be done wirelessly, so that they can be loaded into the chamber using standard wafer loading robotics. Finally, sensors must be designed that are able to operate with low power, occupy a small volume, and operate without perturbing or contaminating the process environment.

Several sensor wafers have been designed, fabricated, and tested. The latest results from these tests are presented in this paper. This work is divided into two areas: (1) sensor development, and (2) on-wafer infrastructure, including power, communications, and isolation. For the first area, film thickness and temperature sensors have been developed and tested. For the second area, wafers employing infrared communication, batteries, and epoxy isolation have been developed and tested.

The outline of this paper will be as follows: First we will discuss the development of new sensors and we will show the latest results obtained with these sensors. The next section will discuss the development of an autonomous sensor wafer. In the last section we will present our conclusions and we will discuss the obtained results.

SENSOR DEVELOPMENT

A film thickness sensor utilizing a van der Pauw sheet resistance measurement structure was designed (see Figure 1). This sensor measures the sheet resistance of a slab of doped polysilicon, and infers thickness based on the known resistivity, as shown by the following equations:

$$\frac{r}{t} = \frac{p}{\ln(2)}\frac{V}{I} \quad \Rightarrow \quad t = \frac{\ln(2)}{p}\frac{I}{V}r$$

where V and I are the measured current and voltage, *r* is the polysilicon resistivity, and t is the sensor thickness. Therefore, when etched, the structure's thickness changes, giving an estimate of the etch-rate.

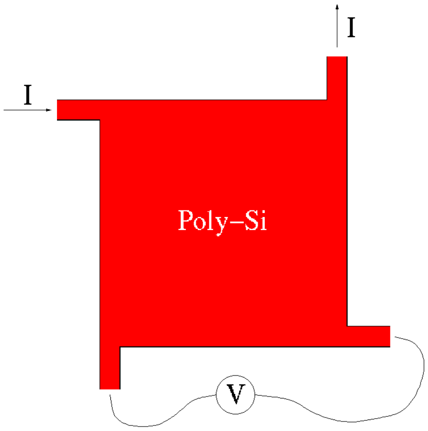

Figure 1. Van der Pauw sheet resistance measurement structure.

However, because the resistivity of polysilicon is a strong function of temperature, this type of thickness sensor is highly temperature sensitive. Therefore, a similar structure, isolated from the etch environment, is used to measure the resistance shift due to temperature, and this shift is used to thermally compensate the etch sensor. For this sensor, it is assumed that the temperatures of the two sensors are identical. This is most likely a good assumption, given that they are only ≅500µm apart, and that the isolated sensor is only shielded from the plasma by a 1µm layer of oxide.

Figure 2 shows data taken by this set of sensors during a polysilicon etch process in XeF_2 gas. XeF_2 is an isotropic gaseous polysilicon etchant. The top trace in the figure shows both the raw, uncompensated output of the film thickness sensor, as well as the thermally compensated film thickness. The bottom trace shows the sensor temperature, as measured by the temperature sensor. From this plot, it can be seen that the raw thickness output of the thickness sensor varies due to temperature fluctuations; however, the temperature sensor information can be utilized to compensate for this effect quite well. Figure 3 shows quite accurately the film thickness during etching. From independent film thickness measurements using a reflectometer, the accuracy and repeatability of this sensor were determined to be ±46Å and ±13Å, respectively.

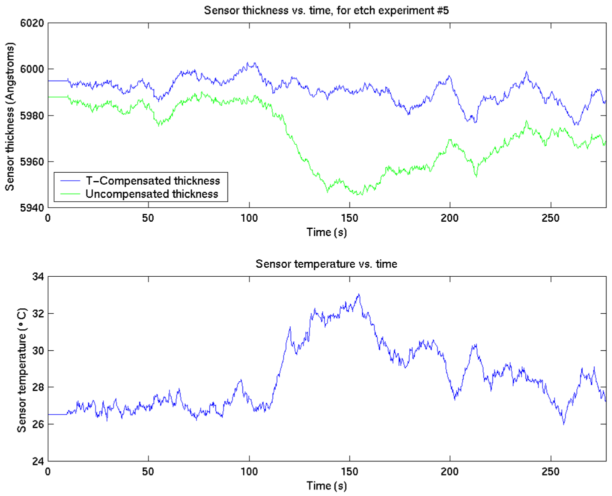

Figure 2. Sensor output during a XeF_2 etch process. The top plot shows the compensated and uncompensated film thickness measurements, and the bottom plot shows temperature.

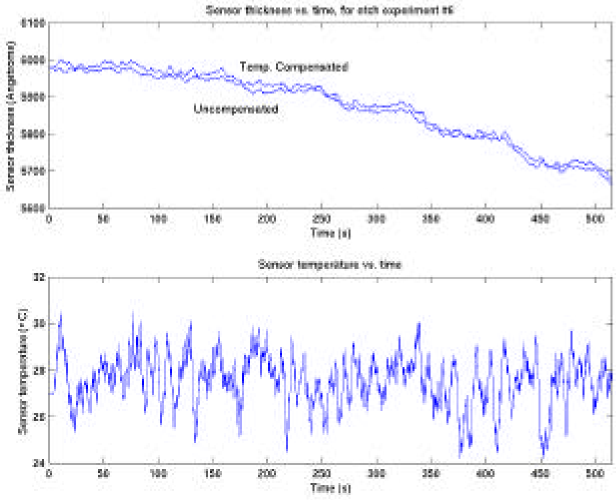

Figure 3. Sensor output during another XeF_2 etch process.

POWER, COMMUNICATIONS, AND ISOLATION

Before the thickness sensors could be tested, the lid of the XeF_2 chamber had to be modified to allow a direct wire connection between the sensors and a computer. However, this type of modification to the processing tool is not desirable, as it limits the application of sensor wafers. Therefore, in order to obtain real-time data from wafer sensors in commercial processing tools it is necessary to develop a method that does not require process chamber modification. Most processing tools have a small viewport to provide direct visual contact with the wafer being processed. This viewport allows the use of modulated light emission for communication.

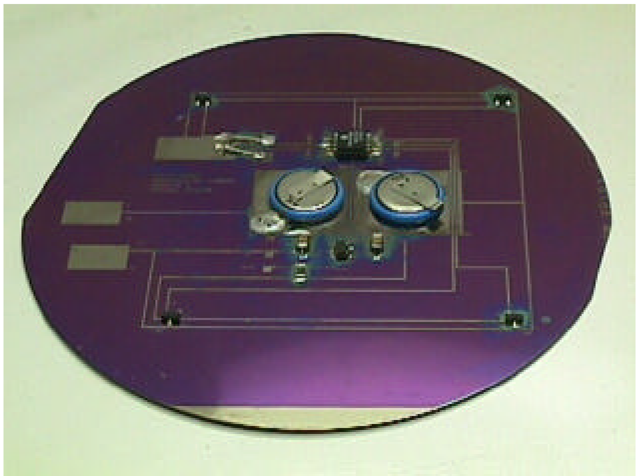

Figure 4. Picture of 4" temperature sensor wafer prior to epoxy isolation.

An autonomous sensor wafer needs onboard power, sufficient for several minutes of operation, and wireless communications to tranmsit the obtained data to the outside world. The surface topology of this wafer must be kept to a minimum, to make it transparent to the wafer handling robotics. Isolation of the sensor wafer is very important to avoid contamination of the processing tool, and also to protect the on-wafer electrical componenes from malfunction due to harsh processing conditions such as high temperatures and plasma.

To test the different options for communications, power, and isolation, a temperature sensor wafer was built with standard off the shelf components that are surface mounted to a "host" wafer. This requires only minimal processing of the host wafers to create metal interconnections, and allows flexibility in testing different configurations and sensors.

Figure 4 shows a picture of one of the temperature wafers. Lithium button cell batteries (3Volt, Sanyo ML1220) provide power to the wafer. A microprocessor (Microchip PIC12C672) gathers data from 4 temperature sensors (National LM61CIM3), encodes this information into a 9600 baud signal, and sends it out via an Infrared light emitting diode (Ir-LED) to the outside world. Temperature information from the wafer is transmitted twice a second. The total current drawn by the circuit is 1 mA with peaks up to 3 mA during data transmission.

A calibrated bake plate was used to test the functionality and performance of the temperature sensor wafer. Testing has shown that this wafer can easily produce repeatable temperature measurements during many cycles up to 150ºC. The button cell batteries allow 11 hours of autonomous operation while cycling between room temperature and 120ºC.

A calibrated temperature wafer has been used to measure the thermal transients experienced by a wafer when placed onto and removed from a bakeplate by automated robotics. These experiments were conducted on an SVG Developer track. Figure 5 shows a test during which the wafer was placed onto a 120ºC hot plate by robotics, left there for 30 seconds, and then moved to a 25ºC chill plate. The wafer heats up uniformly; however, cooling results in variation among settling times due to the distribution of thermal mass and the arrangement of the sensors on the wafer.

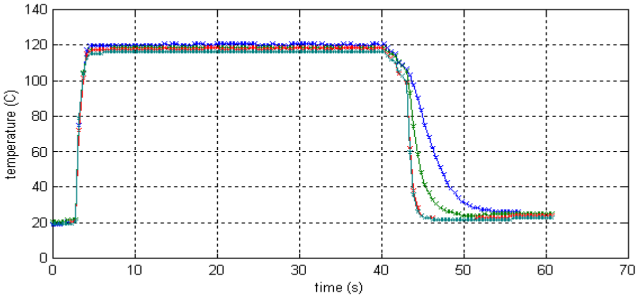

Figure 5. Temperature data during run through SVG developer track.

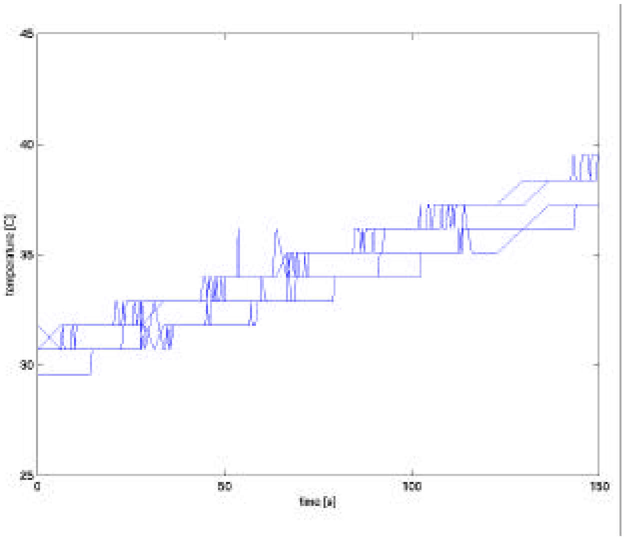

Figure 6. Temperature data during plasma etch process.

One of the goals of this project is to operate a sensor wafer inside a harsh environment such as a plasma chamber. Experiments were therefore conducted in an IPC Plasma Barrel Reactor, which is used for ashing photoresist, and for etching oxide and nitride. It has a maximum RF power output of 300W, and can generate both O_2 and SF_6 plasmas. The wafer was covered with a layer of Ir-transparent epoxy to shield it from the harsh environment. Tests were conducted in O_2 plasma at 0.76 Torr and RF power up to 100W.

Figure 6 shows the temperature sensor output for constant RF power of 100W. As expected, the temperature of the wafer increases slightly over time. These results prove that properly designed electronics can successfully operate and communicate inside of a plasma. Future research will focus on more advanced isolation schemes, which do not significantly increase the thickness of the sensor wafer.

One of the challenges in this project is to minimize the overall power consumption of the circuitry on the wafer, as this will allow the use of smaller batteries, which will result in a reduced surface topology. Therefore, in order to reduce the current drawn by the circuitry, a more advanced communication scheme has been developed in which the Ir-LED has been replaced by a micromachined Grating Light Modulator (GLM) [2,3].

A GLM consists of an array of micromachined silicon beams (arranged into a grating) suspended above a silicon substrate. A voltage difference between the grating and the substrate generates an eletrostatic force, which pulls the suspended beams down (see Figure 7). The grating diffracts a laser beam, which is focused onto the grating. The intensity of the diffracted light changes when the beams are pulled towards the substrate, and this change can be detected.

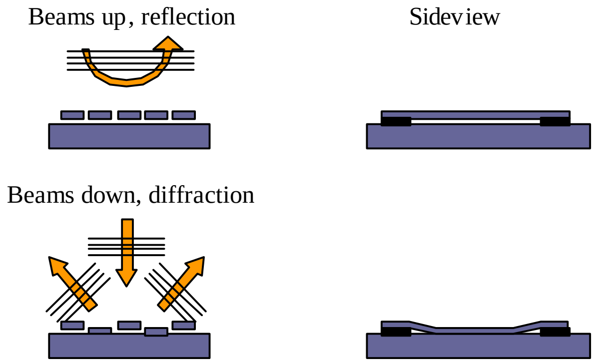

Figure 7. Schematic of GLM operation.

The Ir-LED is an active component; i.e. it actively sends out data, drawing current from the batteries. The GLM, on the other hand, is a passive component; i.e. its state, which can be detected from the outside world via a laser beam, is either low or high and no additional current is drawn once the GLM reaches a particular state. The only current drawn during data transmission is due to charging of the extremely small capacitances between the beams and the substrate. As a result, the current drawn by the GLM is negligible compared to the LED and the rest of the circuitry [4]. Both the protrusion above the surface and the thermal mass are significantly reduced with the GLM.

Lithium button cell batteries have been used to provide power to the circuitry. However, these batteries have a significant influence on the surface topology and thermal mass of the sensor wafer. Therefore we are currently working on a thick wafer (700µm) in which a 500µm pit is etched. In this pit one 4V thick film battery is fabricated to substitute for the thick lithium button cell batteries on top of the wafer surface.

DISCUSSION OF RESULTS AND CONCLUSIONS

The results presented in this paper show that the sensor wafer concept is both valid and feasible. Future work will involve different sensors, as well as testing in various production process chambers. In addition, more advanced batteries and isolation schemes will be explored, as will methods for reducing the surface topology imposed onto the wafer by the components.

ACKNOWLEDGEMENTS

This work was supported by the UC-SMART program under contract #SM97-01, and by the following participating companies: Advanced Micro Devices, Atmel Corp., Applied Materials, Asyst Technologies, BOC Edwards, Cymer, Etec Systems, Intel Corp., KLA-TENCOR, Lam Research Corp., Nanometrics, Nikon Research Corp., Novellus Systems, Silicon Valley Group, and Texas Instruments. All fabrication work was done in the UC Berkeley Microfabrication laboratory.

REFERENCES

[1] D. Fisher, M. Freed, C. Spanos and K. Poolla, "Autonomous Micro-sensor Arrays for Process Control of Semiconductor Manufacturing Processes", *Proc. 38th IEEE Conf. Decision and Control*, Phoenix, AZ, pp.4179-4184, 1999.

[2] O. Solgaard, F. S. A. Sandejas, D. M. Bloom, "A deformable grating optical modulator", *Optics Letters*, vol. 17, no. 9, pp. 688-690, 1 May 1992.

[3] D.R. Pedersen, O. Solgaard, "Free-Space Communication Link Using a Grating Light Modulator", *Proc. 1999 Intl. Conf. Solid-State Sensors and Actuators (Transducer '99)*, pp. 800-803, Sendai, Japan, June 7-10, 1999.

[4] M.V.P. Krüger, M.H. Guddal, R. Belikov, A. Bhatnagar, O. Solgaard, C. Spanos and K. Poolla, "Low-Power Wireless Readout of Autonous Sensor Wafer using MEMS Grating Light Modulator", Proc. IEEE/LEOS Intl. Conf. Optical MEMS, Kauai, HI, August, 21-24 2000.