Passive Wireless Monitoring of Wafer Cleanliness During Rinsing of Semiconductor Wafers

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Abstract—Semiconductor facilities consume large amounts of water, most of which is used for rinsing of wafers during cleaning steps. To optimize water use, real-time and in situ monitoring of wafer cleanliness during rinsing is necessary. Yet no prior art is real-time and in situ. In this paper, we present a passive wireless sensing system capable of measuring the residual contamination on the wafers in real-time and in situ. The wireless system consists of a micromachined Electro-Chemical Residue Sensor (ECRS) and wireless transponder circuitry based on RFID technology. The ECRS measures the impurities concentration of the water inside micro-features during the rinsing processes. The sensor reading is converted to a frequency by the on-wafer transponder and remotely logged through a wireless link between two coupled inductors, while the transponder captures power from the remote RF signal: a battery-free system. A prototype system was fabricated and its frequency output was characterized by using sodium chloride solution ranging from 190 ppb to 6 ppm. The measured wireless chemical sensor system has a relative uncertainty of less than 1% in the concentration range.

Index Terms—Passive sensing, rinsing monitoring, wafer rinse, water saving, wireless sensing.

I. INTRODUCTION

A SEMICONDUCTOR facility consumes a large amount of water, 4 to 10 million liters per day [1]. More than 80% of the consumed water is used for wafer rinsing after chemical cleaning, necessary to remove cleaning chemicals prior to the subsequent processing steps [2]. Control of the rinse process is currently performed by ex situ measurement of remaining contaminants [3] or by monitoring the resistivity of the effluent [4]. The former method measures the remaining contaminants on the wafer and can only be performed after the rinse and dry processes are complete. Such ex situ measurements do not properly elucidate the dynamics of the rinse process. The latter approach monitors the effluent and does not provide contaminant concentration on the wafer surface, where it actually matters.

Hence, current rinsing processes are generally based on experience and guesswork. As a result, expensive high-purity deionized water is usually overused to ensure complete rinsing. Moreover, it is difficult to monitor the cleanliness inside high aspect ratio micro-features, which are often present in semiconductor and microelectromechanical systems (MEMS) devices. These high aspect ratio micro-features are the bottleneck of the rinsing process. This motivates our research work: real-time and in situ monitoring technology for optimizing and controlling the rinsing process for patterned wafers.

Previously, we have developed a micromachined Electrochemical Residue Sensor (ECRS) to monitor cleanliness of wafers [5], [6]. A cross-section schematic of the ECRS is shown in Fig. 1(a). The sensor is a micromachined resistivity sensor. It features a dielectric layer covering the electrodes which distinguishes it from a traditional micromachined resistivity sensor with bare electrodes [7], [8]. With the thick covering dielectric layer, the ECRS measures the impedance of fluid inside high aspect ratio micro-features which mimics the cleanliness of patterned wafers. The ECRS requires complementary circuits to read and analyze. Since the electrical wires, connectors and batteries do not survive the cleaning chemistries used during semiconductor manufacturing, it is preferable to have the monitoring system to be wireless, passive (remotely powered) and integrated.

In this work, we present a prototype system that extends a RFID technology to read out the ECRS data, as shown in Fig. 1(b). It allows real-time, in situ, passive and wireless monitoring of wafer cleanliness. The output of the ECRS is converted to a frequency via an on-wafer oscillator and transmitted to outside reader by passive transponder circuitry via inductive coupling. This new tool may offer new rinse recipes with low resource usage and significant cost savings for semiconductor facilities [5].

This paper is organized as follows. In Section II, the overview requirements and system architecture are described. Decomposed designs of each element are presented and discussed in Section III. In Section IV, we show the measurement results of a prototype wireless system and related system performances are discussed. Finally, the conclusion remarks are presented in Section V.

II. SYSTEM OVERVIEW

The specifications of the rinsing process monitoring are listed in Table I. The ECRS operates at low concentration (10 ppb ~10 ppm), corresponding to high impedance (in the order of 1 kΩ ~ 100 kΩ) between the two electrodes [6]. Fig. 2 shows the characterized impedance profile for corresponding impurity
concentrations using the ECRS. The “wafer clean” is evaluated when the impurity concentrations is less than $10^{-6}$ mol/m², (semiconductor foundries have their own specifications, the number used here serves only as an example) corresponding to the impedance of higher than 200 kΩ. Based on the rinsing profile, the rinsing recipe could be optimized and a customized threshold impedance could be assigned to determine the rinsing end point accurately.

The impedance of the ECRS is modulated and wirelessly transmitted by inductive coupling (near-field coupling) as it is simple and widely applied in RFID applications [9], [10]. In our system, we chose the widely allowed and the lowest frequency band, around 13.56 MHz, among the Industrial Scientific Medical (ISM) bands, since inductive coupling is more effective at lower frequency [11], [12].

Similar to widely adopted RFID schemes [13]–[15], the carrier is modulated by resistive modulation. Other modulation methods exist including capacitive modulation, in which a capacitor is added in series with the switch to modulate carrier phase. However, the capacitive modulation involves a complex architecture and has lower target signal power [16]. The schematic of the resistive modulation in our wireless system is illustrated in Fig. 1(c). In situ monitoring is performed from the measurement of the ECRS, while real-time wireless data transfer is enabled by the RF transponder circuitry. The ECRS measures the impurity concentration of the rinsing water through its electrical impedance ($Z$). The oscillator converts measured impedance ($Z$) to the oscillation frequency ($f(Z)$). The oscillator controls the load modulation switch, in parallel to the secondary inductor ($L_2$). As a result, the load of $L_2$ changes with the frequency, $f(Z)$. Due to the load modulation, a modulated signal is generated and transmitted wirelessly to the primary inductor ($L_1$). The signal received at the reader is demodulated by either spectrum analysis or a demodulator to obtain the oscillation frequency, $f(Z)$. Using a calibrated curve, the impurity concentration is extracted from $f(Z)$. All necessary power is harvested from the external carrier. The rectifier generates a DC voltage to supply the oscillator.
Impedance model of the sensor could be developed based on (1). Details in modeling are discussed in [5] and [6]. The frequency characteristics of the ECRS impedances for different concentrations could be obtained by applying sensor parameters in (1) and plotted in Fig. 3(b). $C_{dl}$ dominates the impedance at low frequency, while the impedance is dominated by $C_{u}$ and $C_{l}$ at high frequency. Only at intermediate frequency is the impedance dominated by the solution concentration sensitive term, $R_{tr}$. In the low-frequency range, which is dominated by $C_{dl}$, the impedance also varies with concentration. The Gouy-Chapman model states that $C_{dl}$ stems from two layers: the Stern layer and the diffusion layer [17]. The capacitance of Stern layer ($C_{stern}$) is independent of concentration, while capacitance from diffusion layer ($C_{diff}$) varies with solution concentration since the effective thickness of the layer, the Debye length, is a function of the concentration. However, the sensitivity of $C_{dl}$ to the impurity concentration is smaller than that of $R_{tr}$, as illustrated in Fig. 3(b), therefore, we chose $R_{tr}$ as the target sensing parameter.

The ECRS is designed to maximize the width of the intermediate frequency band where $R_{tr}$ dominates the impedance. This is achieved by increasing $C_{dl}$ and decreasing $C_{u}$ and $C_{l}$. Decreasing $C_{u}$ and $C_{l}$ is limited because it is not feasible to deposit a very thick dielectric film. Control of $C_{dl}$ is more feasible as it is proportional to the area of liquid-electrode interface. To increase the interface area and thereby increase $C_{dl}$, the sensor electrodes are elongated in an interdigitated pattern as shown in the scanning electron micrograph (SEM) in Fig. 3(c). The optimized sensor has a working frequency range of a few hundreds hertz to a few tens of kilohertz.

### B. Oscillator

The oscillator converts the ECRS impedance to the oscillation frequency. As shown in Fig. 4(a), the oscillator output charges/discharges capacitor $C_3$ through the ECRS. $R_1$, $R_2$ and $R_3$ are biasing resistors and generate a reference voltage ($V_{ref}$) at the non-inverting input of the amplifier. The oscillations of voltages are illustrated in Fig. 4(b). When the output is high, $V_{dhl}$, the reference voltage is at $2V_{dhl}/3$. Then, $C_3$ is charged

$$V_{C3}(t) = V_{dhl} \left(1 - \frac{2}{3}e^{-t/\tau}\right) \quad (2)$$

where $\tau$ is the RC time constant resulting from $C_3$ and the impedance of the ECRS. When $C_3$ is charged to nearly $2V_{dhl}/3$, the amplifier output becomes low, 0 V. Then, $C_3$ is discharged through the ECRS. During the discharging phase, the reference voltage drops to $V_{dhl}/3$ and voltage of $C_3$ becomes

$$V_{C3}(t) = \frac{2}{3}V_{dhl}e^{-t/\tau}. \quad (3)$$

When the voltage of $C_3$ approaches $V_{dhl}/3$, the amplifier output becomes high and thus repeats charging and discharging. From (2) and (3), the time $t_r$, for $C_3$ to be charged to $2V_{dhl}/3$ and the time $t_f$, for $C_3$ to be discharged to $V_{dhl}/3$ can be calculated as

$$t_r = t_f = \tau \ln 2. \quad (4)$$
Since \( \tau \) is a function of sensor impedance \( (Z) \), the oscillation frequency is a function of the ECRS impedance

\[
\frac{1}{f(Z)} = \frac{1}{(2\pi (Z \ln 2))}.
\]

C. Inductive Coupling

The frequency-encoded ECRS impedance data is transferred to the reader via inductive coupling between the inductors at both the reader and transponder \( (L_1 \) and \( L_2 \)). The operating principle of the data transfer is described using the system impedance model shown in Fig. 5. If the impedance change of \( L_1 \) resulting from the coupling to \( L_2 \) is modeled as equivalent impedance \( (Z_t) \), the total impedance \( Z_0 \) at the reader side can be expressed as [11]

\[
Z_0 = R + R_{L1} + j\omega L_1 + \frac{1}{j\omega C_1} + Z_t
\]

where \( \omega \) is the working frequency, \( R \) is the resistor to measure the target signal, \( R_{L1} \) is the resistance of \( L_1 \) and \( C_1 \) is the series capacitor that tunes the reader’s resonance to 13.56 MHz. When the switch is off, \( Z_t \) becomes

\[
Z_{t_{off}} = \frac{\omega^2 k^2 L_1 L_2}{R_{L2} + j\omega L_2 + \frac{R_{rec}}{1+j\omega R_{rec}C_2}}
\]

\[
k(z) = \frac{\sqrt{\tau_1^2 \tau_2^2}}{\sqrt{\tau_1^2 \tau_2^2 + \tau_1^3}}
\]

where \( k \) is the coupling coefficient between the two inductors, \( R_{L2} \) is the resistance of \( L_2 \), \( R_{rec} \) is the input resistance of the rectifier, \( \tau_1 \) and \( \tau_2 \) are the side lengths of the two inductors and \( z \) is the distance between the two inductors. When the switch is on, \( Z_t \) becomes

\[
Z_{t_{on}} = \frac{\omega^2 k^2 L_1 L_2}{R_{L2} + j\omega L_2}.
\]

As a result, the voltage across \( R \), \( V_R \), varies with the switching frequency \( f(Z) \). The amplitude variation of \( V_R \) is a function of the power of the target signal and is proportional to the difference between \( Z_{t_{off}} \) and \( Z_{t_{on}} \).

Obviously, to obtain stronger target signal, it is desired to have large impedance difference between \( Z_{t_{off}} \) and \( Z_{t_{on}} \), which is a function of the quality factor of the transponder inductor. \( Z_{t_{off}} \) can be expressed in terms of the quality factor of \( L_2 \): \( Q_2 \):

\[
Z_{t_{off}} = \frac{\omega^2 k^2 L_1 L_2}{R_{L2} + \frac{\omega^2 L_2^2}{R_{rec}}} = \frac{\omega^2 k^2 L_1 L_2}{\frac{\omega^2 L_2^2}{Q_2}} = \omega k^2 L_1 Q_2
\]

\[
Q_2 = \left( \frac{R_{L2}}{\omega L_2} + \frac{\omega L_2}{R_{rec}} \right)^{-1}.
\]

Comparing (8) with (9) shows that in order to increase the difference between \( Z_{t_{off}} \) and \( Z_{t_{on}} \), \( Q_2 \) needs to be high, which could be achieved by decreasing \( R_{L2} \) and increasing \( R_{rec} \).

D. Rectifier

The rectifier converts RF input power to a DC voltage, which powers the oscillator. Most RFID designs have a voltage doubler as a rectifier [18], [19]. The input impedance of a traditional doubler, the impedance of a forward biased diode, is small, a few hundreds of Ohms. Such small impedance greatly decreases the transponder’s quality factor (\( Q_2 \)) and consequently lowers the target signal power, as shown in (7)–(9). Therefore, we put a large resistor (\( R_6 \) in Fig. 6) in series with the diode network. \( R_6 \) cannot be too large as a large resistor decreases the voltage drop across the diode network \( (V_{diode}) \) and consequently decreases the DC voltage at the output of rectifier. Voltage doublers can be
cascaded to obtain a higher DC output. However, the number of the stages directly affects the rectifier efficiency and DC output voltage. Generally higher DC output can be achieved by increasing the number of stages, yet compromising rectifier efficiency [16]. In practice, two to four stages are typically used. In our design, we chose a two-stage rectifier to achieve relatively high efficiency.

IV. CHARACTERIZATION AND DISCUSSION

The fabrication of the wireless sensor system uses a standard micromachining technology. On an oxidized silicon substrate, polysilicon and silicon dioxide layers were deposited by LPCVD (Low Pressure Chemical Vapor Deposition). Both layers were patterned by RIE (Reactive Ion Etching) using the same mask to form desired micro-features and electrodes of the sensor. The secondary inductor was electroplated to reduce its resistance for high Q. The primary inductor, oscillator, rectifier and necessary discrete components were implemented on a PCB. Soldered wires were used to connect the secondary inductor to the transponder circuitry and to the ECRS. The assembled on-wafer transponder including the secondary inductor, ECRS and transponder circuitry is shown in Fig. 7.

The characterization of the system was performed in two stages: characterization of the ECRS and characterization of the overall wireless system with a controlled calibration solution. The ECRS was measured at 10 kHz where the resistance of solution inside the micro-feature (R_{s}) dominates the impedance. The characterization was performed with sodium chloride solution with concentration from 190 ppb to 6 ppm. Concentrations less than 100 ppb were not used as the conductivity of low ionic concentration solutions is difficult to control because CO_{2} from the air dissolves in the water and raises the conductivity. Such measurements should be performed in a well-isolated environment, which remains as our future work. Sodium chloride was used to demonstrate the functionality of the system. Different semiconductor foundries have different rinsing recipes. In order to actually implement the wireless system in semiconductor foundries, it is necessary to calibrate the system with specific rinsing solution cocktails. An example of the calibrated curve of the ECRS is shown in Fig. 8(a). The impedance changes from 85.4 kΩ to 44.5 kΩ as the concentration of sodium chloride increases from 190 ppb to 6 ppm. The calibration curve presents the measurements uncertainties of less than 0.3%.

System level characterization was performed with the sodium chloride solution of the same concentration range. The system has a working distance of approximately 5 cm. In the experiment, the distance between the two inductors was set at 1 cm. The RF input was provided by a signal generator with 1 V at 13.56 MHz. The oscillation frequency \( f(Z) \) was measured using a signal source analyzer. A spectrum of the detected signal for 600 ppb NaCl is shown in Fig. 8(b). The oscillation frequency is the frequency difference between the carrier, 13.56 MHz and the first sideband peak. High-order harmonics are generated as the modulation switch is controlled by square wave rather than pure cosine wave. In Fig. 8(c), the measured oscillation frequencies are plotted as the solution concentration varies from 190 ppb to 6 ppm. The measurement uncertainties are within 1%.

The system resolution is a function of RBW (Resolution Bandwidth) of the signal source analyzer. In our measurements, the signal source analyzer, Agilent E5052A, was used, which has a minimum RBW of 1.53 Hz. With the minimum RBW, the detected signal is analyzed from 13.564425 MHz to 13.564525 MHz (100 Hz band), as shown in the embedded figure in Fig. 8(b). The frequency resolution is approximately...
0.4 Hz, which corresponds to a concentration resolution of 20 ppt at a concentration of 190 ppb. However, the price paid to have high resolution is the measurement time. To comprise the measurement time and measurement resolution, we used the RBW of 97.7 Hz in our measurement, which has a frequency resolution of approximately 2 kHz (concentration resolution of 0.4 ppb at a concentration of 190 ppb).

The system was measured a few times with an interval of 12 hours to measurement its reproducibility. Ambient temperature was well controlled within ±0.2 degree. Measurement results are shown in Fig. 9, which shows a system reproducibility of 1.5%. No obvious system drift is observed from these measurements.

Before practical use, temperature effect on the system should be considered. Temperature is known to drift conductivity sensor by 1%–3% per degree [7]. To study the temperature effect, the wireless system was mounted on a hotplate and thermocouples at different places around the system were used to measure and control the temperature within ±2 °C. Temperature was varied from 26 °C to 41 °C with a step of 5 °C. System responses for different concentrations at different temperatures were recorded in Fig. 10. The temperature coefficient of the system was measured approximately 1%/°C. Generally, semiconductor manufacturing is performed in a well controlled environment, temperature fluctuations will not greatly affects the monitoring system. However, if the system is designed to work with large temperature variations, corresponding calibrations at desired temperatures are needed to have a more precise response from the system.

In a complete system, the transponder wafer could be used as a monitoring wafer that undergoes the same procedures as

![Fig. 8.](image1)

![Fig. 9.](image2)

![Fig. 10.](image3)

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance of $L_1$</td>
<td>0.47 μH</td>
</tr>
<tr>
<td>Inductance of $L_2$</td>
<td>1.56 μH</td>
</tr>
<tr>
<td>RF input voltage</td>
<td>1 V</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>13.56 MHz</td>
</tr>
<tr>
<td>Concentration range</td>
<td>190 ppb – 6 ppm (calibrated)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Sensor impedance</td>
<td>85.4 kOhm – 44.5 kOhm</td>
</tr>
<tr>
<td>Measured frequency</td>
<td>3.9 kHz – 7.1 kHz</td>
</tr>
</tbody>
</table>
regular wafers do during the rinsing process. A protective film, e.g., PDMS, epoxy, should cover the circuitry to be protected from chemical attacks. Such a fully functional system can monitor the rinsing progress in real-time and in situ to develop optimized rinsing recipes and consequently large amount of ultrapure water could be saved, up to 40%-50% [5].

V. CONCLUSION

The semiconductor industry consumes a large amount of ultrapure water for rinsing wafers. Current methods are unable to provide real-time and in situ sensing data during rinsing for optimizing and reducing water usage. We present a passive and wireless chemical sensing system prototype to achieve real-time and in situ measurements of water cleanliness via RFID and micromachining technologies. All necessary power is supplied by the RF signal and high accuracy sensing data is transferred wirelessly using inductive coupling. The potential outcome includes saving large amounts of water in semiconductor and MEMS facilities, resulting in environment friendly and cost effective production.

REFERENCES

Junseok Chae received the B.S. degree in metallurgical engineering from the Korea University, Seoul, Korea, in 1998, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor, in 2000 and 2003, respectively.

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Prof. Chae received the First Place Prize and the Best Paper Award at the Design Automation Conference in the student design contest in 2001. He is a recipient of NSF CAREER award.