Process Control of Chrome Dry Etching by Complete Characterization of the RF Power Delivery

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ABSTRACT

In order to fulfil the upcoming requirements for photomasks there is a need for improving the process stability (reproducibility) of the unit processes in photomask fabrication. In order to understand and minimize the etch contribution to the CD stability impedance sensors integrated into the capacitively coupled radio frequency (RF) circuit (bias circuit) have shown a big potential[1,2].

The last step towards a full characterization of the RF properties is the integration of impedance sensors in the inductively coupled RF circuit (source). This kind of sensor measures voltage, current and phase angle for the fundamental (13.56 MHz) and higher harmonics (up to the 5th harmonic).

In this paper we are describing the integration of the Z-Scan sensors into the source RF matchbox and its impact on the RF and CD characteristics of the mask etcher. The central point is the correlation of impedance data to CD data. We will also compare the responses for bias and source impedance measurements.

Keywords: dry-etching, process control, RF sensor, V-I probe, impedance

1. INTRODUCTION

Advancing the double patterning technology critical dimension (CD) mean to target (MTT) requirements for photomasks are getting more and more stringent[3]. In order to achieve these requirements there is a need to identify the process steps contributing to the MTT fluctuations. One of the main contributors is the chrome dry etching process[4]. Changes in etch performance can rarely be correlated to standard tool parameters like process pressure, gas flow etc. which are commonly collected through the tool software.

Other RF and plasma relevant parameters can only be collected with external systems. There is a variety of measurement systems available on the market e.g.:

- Langmuir probe (for measuring basic plasma properties like electron and ion density)
- Hercules[5] sensor utilizing the self excited electron resonance spectroscopy (SEERS) (to determine for example the electron collision rates or the electron density)
- optical emission spectroscopy (OES) (commonly being used for etch endpoint detection)
- Voltage and Current (V-I) probes for example Z-Scan[6] or SmartPIM[6] (collecting RF properties like current, voltage and phase angle for the fundamental frequency and higher harmonics)

State-of-the-art photomask dry etching systems consist of two separate plasma sources commonly referred to as source and bias. While the inductively coupled source power is used to maintain the bulk plasma the capacitively coupled bias power is used to make the plasma more anisotropic. Recent publications showed that bias impedance data collected with a V-I probe provide valuable data that can be correlated with the CD properties of photomasks[1,2].

We are going to expand this concept by integrating V-I probes into both RF circuits (bias and source). This kind of data can either be used for troubleshooting the RF delivery system or for monitoring (and actively controlling) the chrome

Photomask Technology 2008, edited by Hiroichi Kawahira, Larry S. Zurbrick,
Proc. of SPIE Vol. 7122, 71220E · © 2008 SPIE · CCC code: 0277-786X/08/$18 · doi: 10.1117/12.801080

etch process. The advantage of the sensors is that they measure the feedback of the entire system including power loss in contacts, matchbox chamber and plasma. Nevertheless it is not possible to separate the contributions to the overall power loss.

In order to achieve statistically relevant results we collected data from identical products using the exact same process conditions.

2. EXPERIMENTAL

Experimental and production data were collected on an Applied Materials Tetra II chrome dry etch system. This system consists of two plasma sources being controlled separately (figure 1). Both, the capacitively coupled bias power and the inductively coupled source power are driven by a RF generator operating at 13.56 MHz. Impedance matching of the RF supply to the load (chamber and plasma) is done by an Advanced Energy Navigator matching network (matchbox). A so called divider capacitor being integrated into the source matchbox splits the source power into two coils (inner and outer source coil). We integrated two Z-Scans between the outputs of the source matchbox and the inner and outer source coil. The bias matchbox is equipped with a Z-Scan impedance sensor by default.

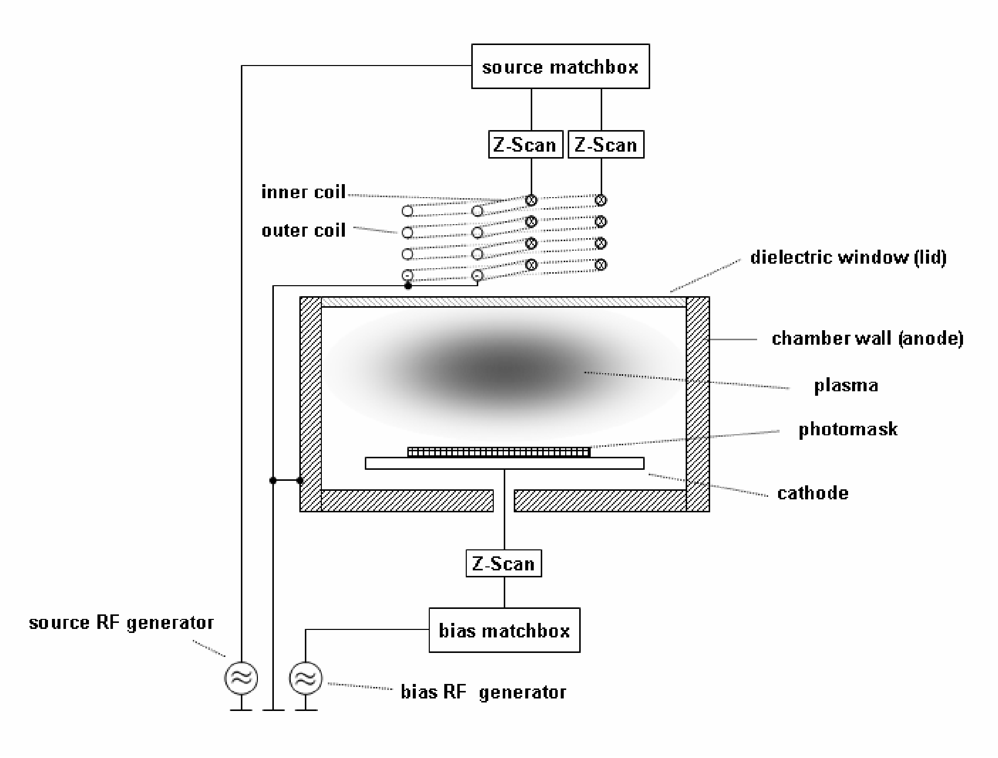

Figure 1: Schematic setup of the plasma etcher with Z-Scans in the source and bias RF circuit

Z-Scan impedance sensors measure RF voltage *V*, current *I* and the phase angle θ (direct sensor signals) for the fundamental frequency (13.56 MHz) and for higher harmonics (up to the 5th harmonic corresponding to five times the fundamental frequency). Harmonics are generated by the non linear response of the RF load. The order of the harmonic will be marked with the index *i*. Resistance *R*, reactance *X* and impedance *Z* (indirect sensor signals) are calculated according to the following equations:

$$R_i = \frac{V_i}{I_i}\cos(\theta) \qquad [1]$$

$$X_i = \frac{V_i}{I_i}\sin(\theta) \qquad [2]$$

$$|Z_i| = \sqrt{|R_i|^2 + |X_i|^2} \qquad [3]$$

With this kind of analysis we are not able to separate the chamber impedance from the plasma impedance. So the presented impedances are always a superposition of the chamber and the plasma impedance. All Z-Scan data shown in this article are mean values taken from the mainetch (the plasma stiking phase was removed).
All source Z-Scan data are being collected in a symphony equipment server (SES) from Pivotal Systems and are fed together with all tool data into an engineering database (EDB) via a SEMI Equipment Communication Standard (SECS) communication (figure 2).

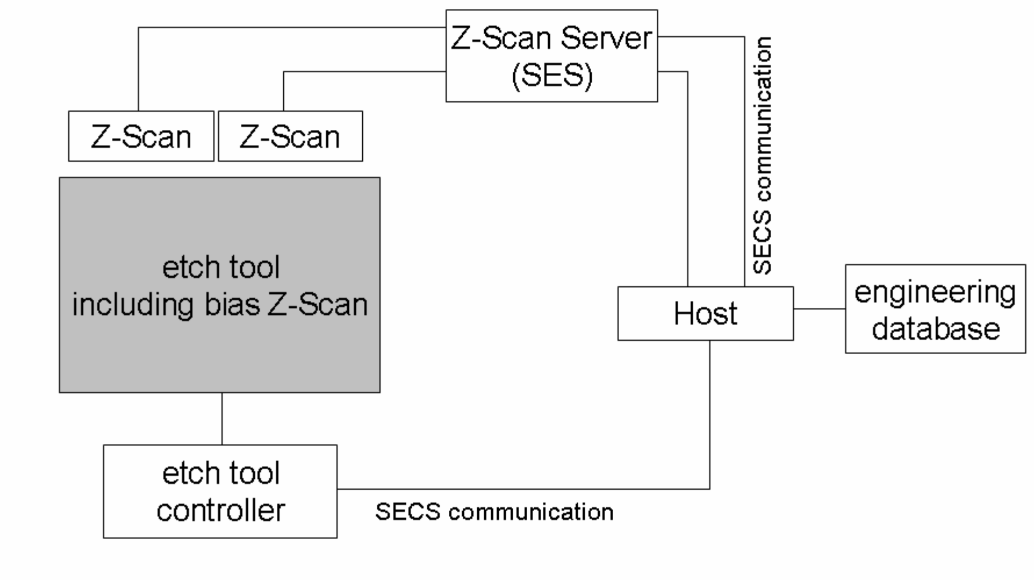

Figure 2: Schematic data infrastructure with source Z-Scans installed

The process being investigated is a standard chrome dry etch process with chlorine and oxygen chemistry. For the process bias investigation we used a half tone phase shift mask (HT-PSM) dedicated for 193nm illumination with a chemically amplified resist (CAR). These masks were exposed with a 50kV electron beam writer. Process bias data are calculated as the difference of the final CD measurement in the phase shifter and the resist CD. For the correlation analysis we took a set of product masks (more than 10 masks) with identical layout. In addition we collected data from a daily monitoring test to understand the long term behaviour of the signals.

3. RESULTS AND DISCUSSION

3.1 Installation of the Z-Scan sensors and description of the sensor output

The Z-Scan sensors are acting as an additional capacitance in the source RF circuit (figure 3). As a consequence the operating point of the source matchbox is shifted by the installation of the Z-Scan sensors and the striking conditions had to be re-adjusted. Before and after the installation we compared the etch results like CD MTT, CD uniformity and CD linearity and there was no significant change observable.

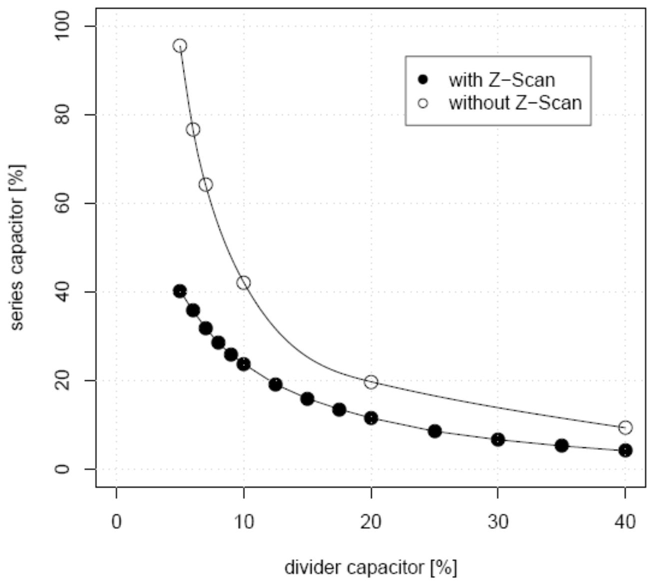

Figure 3: Tuning position of the series capacitor for best impedance matching with and without the Z-Scan sensors in the source RF-circuit as a function of the divider capacitor

Typical measured “direct” Z-Scan signals (current, voltage and phase for all harmonics) for a representative test run are summarized in figure 4. One can see that the 1st harmonic phase angle of both source Z-Scans has a positive value around +90° indicating an inductive coupling of the source power. On the other hand the bias 1st harmonic phase angle is around -90° indicating a capacitive coupling. Compared to the 1st harmonic the voltage and current signals for all higher harmonics are smaller by orders of magnitude. This is indicating that the response of the RF load is nearly linear to the driving force.

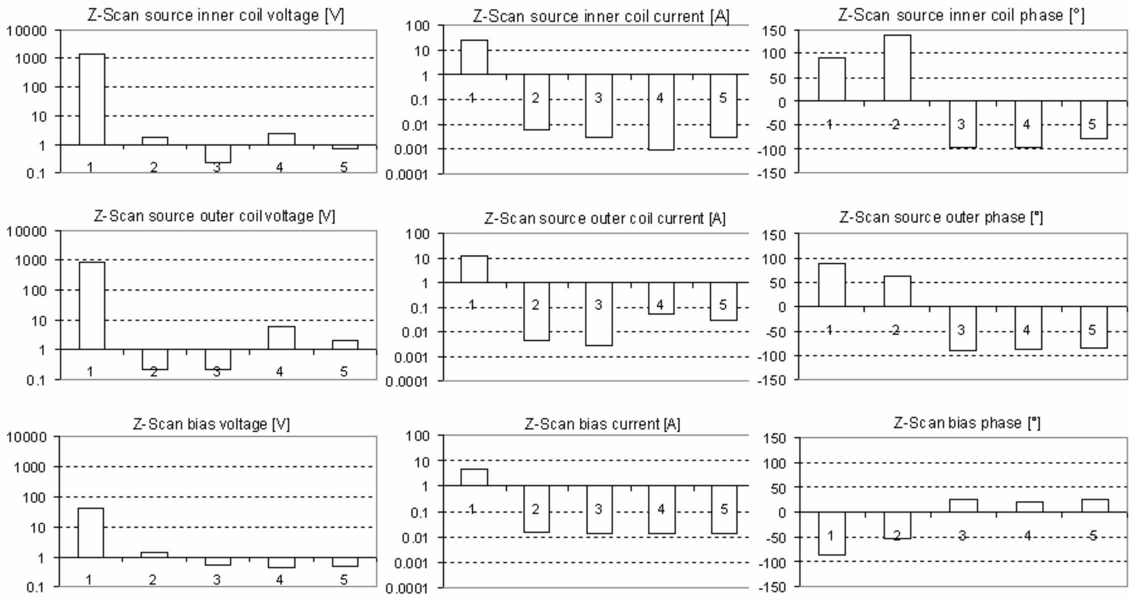

Figure 4: Overview of the direct sensor signals (voltage, current and phase) of the inner source Z-Scan (top row), outer source Z-Scan (middle row) and the bias Z-Scan (bottom row) as a function of the harmonic order for a standard etch recipe. Voltage and current are displayed on a logarithmic scale, phase angle is on a linear scale.

The calculated impedance, reactance and resistance values are summarized in figure 5. In contrast to the direct signals (see figure 4) the strongest response is coming from higher harmonic signals.
The change in sign of the reactance (middle column) from the 2nd to the 3rd harmonic is caused by the change in sign of the phase angle (see figure 4, right column).

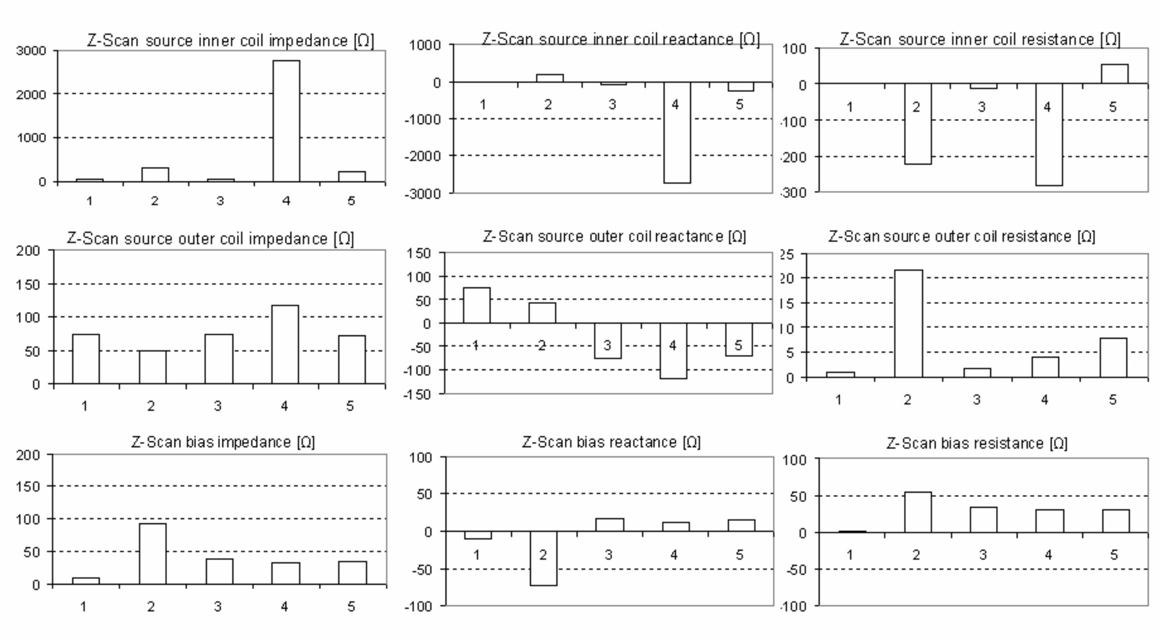

Figure 5: Overview of the indirect sensor signals (impedance, resistance and reactance) of the inner source Z-Scan (top row), outer source Z-Scan (middle row) and the bias Z-Scan (bottom row) as a function of the harmonic order for a standard etch recipe

3.2 Time series of the sensor outputs

Figure 6 shows the day to day variation of selected impedances. Some graphs have pronounced jumps, while others are following a more continuous trend.

- The jumps in the inner source coils impedance (2nd harmonic) coincide with maintenance activities where the complete source setup was moved (figure 6a). The last jump for example is corresponding with a yearly maintenance of the etch tool.
- The inner source coil resistance (4th order) in figure 6b seems to have a higher noise level as well as a higher fluctuation than all the other signals. We will show later on that this resistance correlates fairly well with the process bias.
- In figure 6c a monotonous trend over time can be observed for the inner coil impedance (5th harmonic). It does not seem to be influenced by any of the maintenance activities.
- The bias impedance (1st harmonic) in figure 6d jumps back after the maintenance activity

Generally spoken the inner source coil impedances are more sensitive than the ones from the outer source coil.

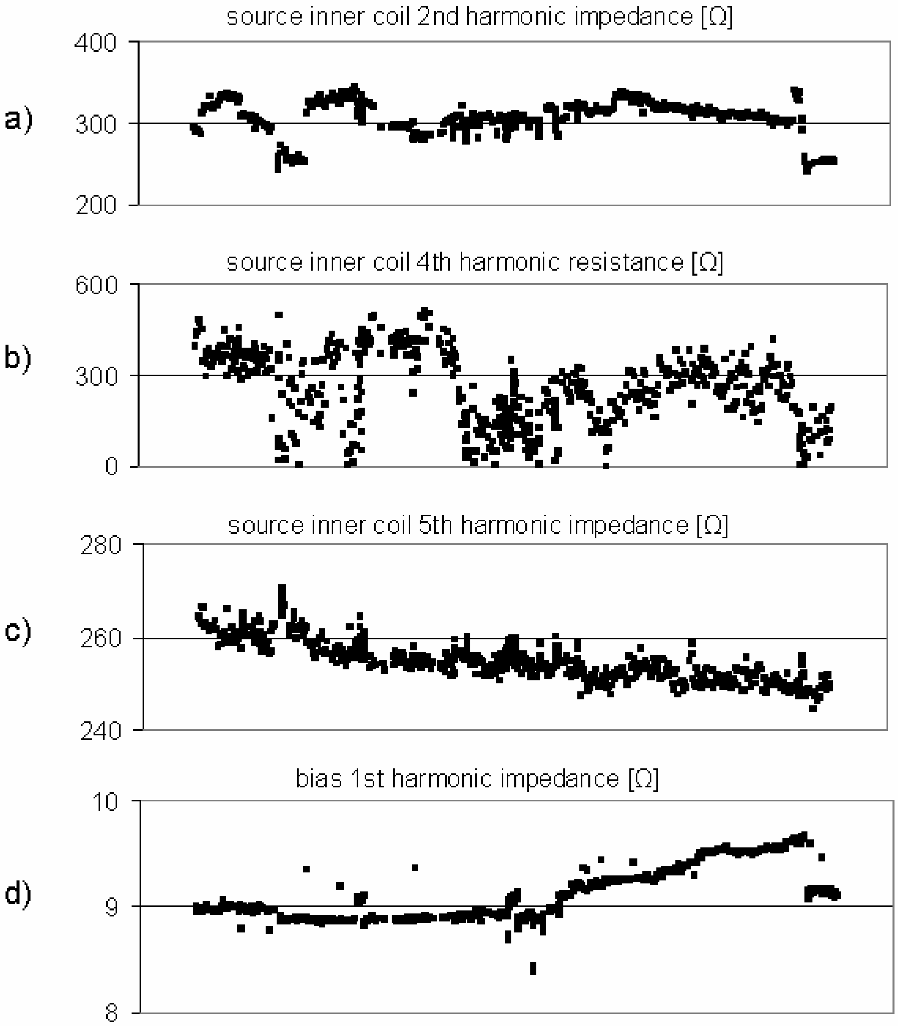

Figure 6: Day to day variation of the indirect sensor signals (impedance and resistance).

3.3 Correlation analysis of sensor signals and mask properties

Finally we will discuss the correlation analysis of the mask properties and the sensor signals. Figure 7a shows the correlation of the photoresist etch rate with the bias apparent power. The apparent power is calculated with the following equation:

$$Q_i = V_i I_i \sin(\theta) \tag{4}$$

The 1st harmonic apparent power of the bias RF circuit is proportional to the DC bias voltage.

Figure 7b shows the correlation of the source impedance with the process bias. Data after the maintenance activity (last jump seen in figure 6a, d) is not contained in these graphs. It still has to be proven if the correlation of the impedance after this maintenance activity matches with the correlation plots in figure 7, or if the models have to be readjusted.

The trend in figure 7a shows a correlation with photoresist etch rate, but it does not show a correlation to other mask parameters. Nevertheless we can not exclude that this signal may show a correlation in case of more significant hardware issues.

The CD relevant correlation is shown in figure 7b. This figure illustrates the dependence of the process bias on the 4th harmonic of the source resistance. This is the first CD relevant parameter being identified for this hardware configuration and process setup.

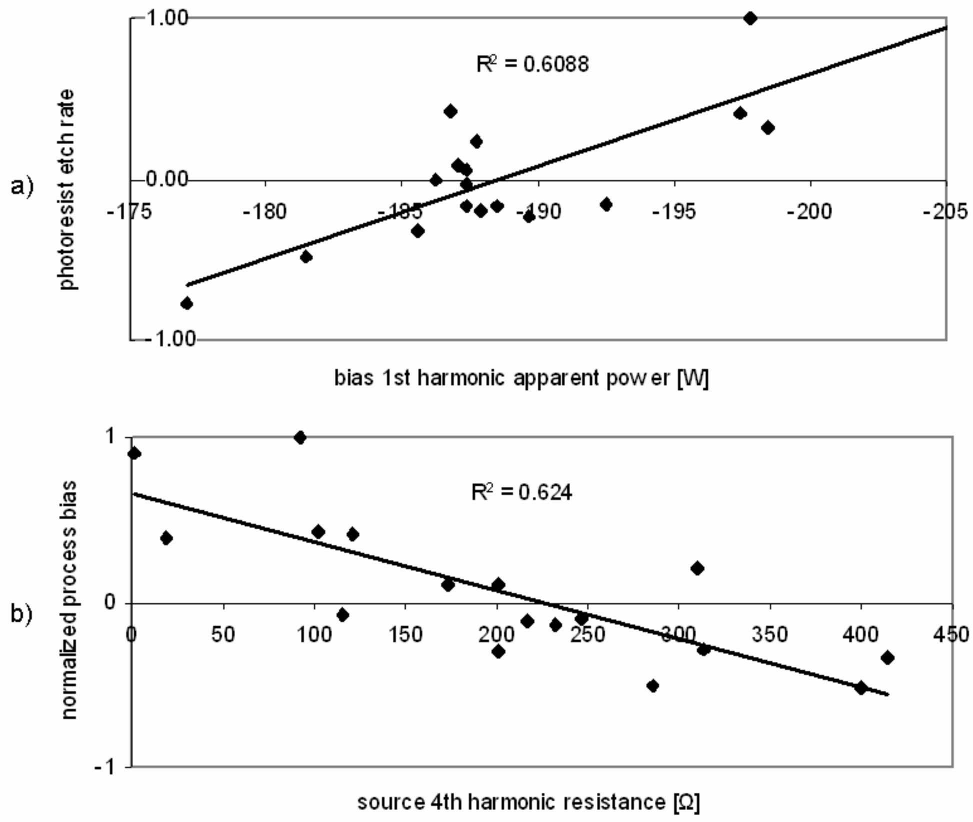

Figure 7: Correlation of normalized photoresist etch rate and bias apparent power (a) and normalized process bias and source resistance (b)

4. CONCLUSIONS

A full RF characterization (source and bias) utilizing the higher harmonic signals is a powerful method for maintaining and controlling the chrome dry etch process. Comparing our data to recently published work[1,2] we conclude that the dependencies observed are strongly linked to the tool and process setup.
There is a demand for detecting and understanding the error sources detracting the process stability and repeatability[8]. We want to encourage the equipment suppliers to integrate such kind of process stability control for photomask processing equipment.

5. ACKNOWLEDGMENTS

AMTC is a joint venture of AMD, Qimonda and Toppan Photomask and gratefully acknowledges the financial support of the Federal German Ministry of Education and Research (BMBF) under contract No. 01M3154A (Abbildungsmethodiken fuer nanoelektronische Bauelemente).

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