

A New Surface Analysis Method for Semiconductor Manufacturing, based on Surface-Potential Measurements

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Abstract - The introduction of new materials into the process flow, the continuous reduction of device sizes, and the change in thermal budgets from new technologies, all require a continuous assessment and, if necessary, a development of new monitoring capabilities for defects and contamination in the semiconductor industry. Besides the detection of physical defects with optical wafer inspection systems, the detection of thin monolayer contamination, so called 'non-visible' residues (NVR), requires increasing attention. These surface contaminations change the local chemical state of the substrate surface and can be detected by the measurement of the surface potential difference across the wafer. In this study, we describe a method for improving analytical capabilities for contamination control in support of process engineering and development.

I. INTRODUCTION

The analytical support at the end of a detection and classification chain provides the elemental analysis for a definition of a hypothesis in a root cause analysis, or for process improvements, or decisions in process control procedures. In this study, we will assess the process from detection of defects and contaminations to the final elemental analysis, and will describe possible improvements based on an evaluation of a new wafer inspection methodology.

The monitoring of defect density on product wafers in semiconductor frontend processing is done mainly by optical inspection in the production line. A subsequently desired elemental analysis of certain selected defects or particles can be performed using energy dispersive spectroscopy (EDS) in a scanning electron microscope (SEM), typically located in the clean room as well. If necessary, further analysis can be done using the laboratory based analytical toolset, such as auger electron spectroscopy (AES) or time-of-flight secondary ion mass spectroscopy (ToF-SIMS). The prerequisite of a navigation possibility on the wafer is usually implemented in modern lab tools.

Hence, starting from the defect map from an optical inline inspection tool one has a tool for classification and a direct path to the laboratory based analysis. The detection of a thin monolayer non-visible residue (NVR) defect on the surface of product wafers is very difficult for optical inspection systems or often not possible at all, as these NVRs do not scatter light.

The situation is different for contamination analysis. The contamination control, particularly for metal impurities, is based mostly on vapor phase decomposition (VPD) followed by a suitable detection method, e.g. ion-coupled-plasma-mass-spectroscopy (ICPMS) or total reflection X-ray fluorescence (TXRF) on test wafers. In this case, no spatial information on the distribution of the impurities is available.

Hence, a locally increased contamination level on the wafer with the real potential to cause device failures may be overshadowed by the averaging effect over the whole wafer. Point based laboratory methods, such as ToF-SIMS, are typically not suited for full wafer analysis as mapping with a sufficient analyzed area would be far too time consuming.

Table 1 shows a summary of the limitations with both optical inspection and surface analysis techniques with regards to detecting monolayer type NVR defects.

TABLE I
ASSESSMENT OF OPTICAL AND ANALYSIS METHODS

| | Optical Inspection Capabilities | | Surface Analysis Techniques | |
|------------------------|---------------------------------|-----------------------|-----------------------------|--------------------------|
| | Patterned Wafer Inspection | Bare Wafer Inspection | e.g. VPD (ICPMS/ TXRF) | e.g. TXRF, ToF-SIMS, AES |
| Detection of: | | | | |
| physical defects | X | X | no | X |
| metallic contamin. | local with EDS | local with EDS | full wafer, no signature | local |
| organic NVR | no | no | no | (ToF-SIMS) |
| wafer charges | no | no | no | no |
| Capability for: | | | | |
| spatial signature | defects on product | defects on bare wafer | no | no |
| edge inspection | limited | limited | no | limited |

Following these arguments, we came to the conclusion that there is a gap in contamination control for NVR defects. To close the gap, one should introduce a method which must not necessarily provide qualitative or quantitative elemental information on the contamination. Rather, the primary requirement would be sufficient throughput, spatial resolution in the μm range and of course, in line capability. We came to the conclusion that the detection of these NVR defects on product wafers will be very important for the fulfillment of the detection requirements according to the ITRS roadmap [1].

In this study, we will report on the application of a method fulfilling the above mentioned requirements. We have assessed the capability of the method for applications in both memory wafer fab and backend packaging fab for bond pad or solder ball geometries. The experiments focused on the whole analytical chain from the inline detection of NVR defects to the laboratory analysis, in our case using ToF-SIMS.

II. SURFACE POTENTIAL DIFFERENCE IMAGING

The measurement of work function at the surfaces of semiconductor materials is used for several applications in the semiconductor industry, e.g. gate-oxide quality or material analysis.

As reported in reference [2], the Kelvin Probe can be described as a capacitor consisting of a tip and the wafer surface material as the electrodes with an air gap. The voltage across the capacitor, when both electrodes are connected, is the contact potential. The concept behind the measurement principle of the ChemetriQ® technology is the detection of changes in the chemical state of the surface with the measurement of the contact (aka surface) potential during the movement of the tip across the surface.

The changes in the voltage are equivalent to changes in the surface potential, which are visualized with the scanning surface potential Differential Image as shown in Figure 1(a). All local changes in the surface potential in positive (white) and negative (black) direction are shown in this map. The scan path consists of a concentric ring starting from the outside of the wafer to the center and detects the changes in the surface potential along the complete top bevel edge and the entire interior wafer surface area.

For an improved overview, a visualization of areas with the same surface potential is available with the so called Integrated Image as shown in Figure 1(b), with areas of higher surface potential in white and lower surface potential in black.

For surface potential variation across the wafer, the scanned differential data is combined with absolute surface potential measurements (called ACM mode, or Absolute ChemetriQ Measurement). In this example, measurements were made every few millimeters along a 45° line profile from southeast to northwest. With these discrete data points, the ACM Image is calculated using the QViewer™ software as shown in Figure 1(c). This capability enables comparisons of wafer surface potential or process induced charges [3].

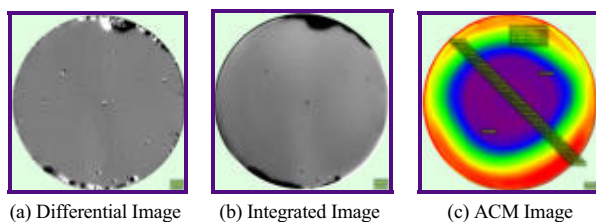


Fig. 1. Imaging Capability using ChemetriQ Inspection

For a determination of the influences from surface topography, the Surface Potential Difference Imaging (SPDI) technique can measure in a second scan using an anti-bias (V_{bias}), to amplify the topography signal. Figure 2 shows the capability to distinguish between NVR defects and surface topography. In this case, some defect signatures (the small dots, ring near center 6:00) are suppressed with the applied bias of 3V which indicates that these signatures are due to topography.

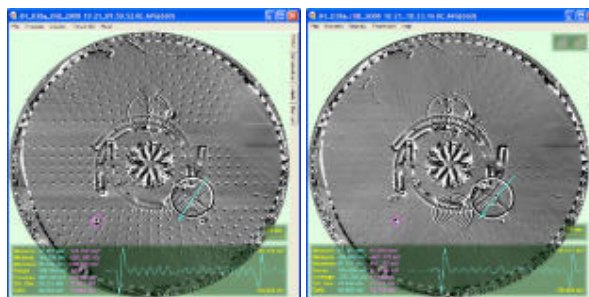


Fig. 2. Imaging Capability of ChemetriQ-3000, right map (with 3V Bias): changes in defect signature for small dots and the ring signature near center 6:00. no changes=chemical states

III. EXPERIMENTS AND RESULTS

As described in the introduction of this study, the evaluation of this new wafer inspection method was motivated by the need for a scanning technology detecting contaminations on a wafer while providing spatial signatures. Due to the specific situation providing support for a wafer fab and a backend line for special packaging methods, the system was located in a material analysis lab.

The experiments were planned according to the typical wafer flow to the analysis lab by collecting test wafers from the wafer fab or specially prepared product or test wafers to perform the evaluation of the system. Compared to established analysis methods like VPD-ICPMS, VPD-TXRF or ToF-SIMS, the SPDI technique should provide additional information for troubleshooting and for the understanding of contamination locations. One additional important point of hypotheses at the beginning of the study was; is it possible to improve the process relevance of in line contamination tests with this new inspection approach?

Two simple examples describe the potential of the SPDI technique for specially designed experiments with bare or patterned wafers for contamination analysis. In Figure 3, the Integrated Image from a bare silicon wafer highlights the differences in the NVR defect between a used and cleaned wafer vacuum tweezers. In Figure 4, the Integrated Image on a patterned product wafer from the backend packaging process highlights residual Aluminum residues on the left side of the wafer where there are 100% open fuses. We will expand on

this example later in the paper using inspection data used to study and optimize the photoresist strip process.

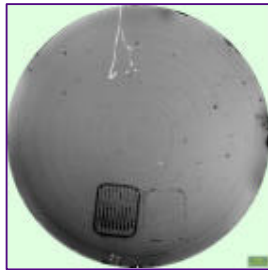


Fig. 3. Integrated Image of a NVR signature from a used (left) and cleaned (right) wafer vacuum tweezers

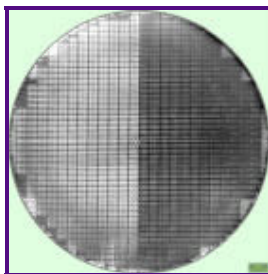


Fig. 4. Integrated Image of a backend wafer with 100% open fuses and remaining Al-residues at left side

IV. DETECTION OF INORGANIC CONTAMINATION

Driven by the introduction of high-K dielectric films in the process flow and the change of integration schemes in new memory technologies, the established contamination control and surface analysis methods require increased attention. The detection efficiency of these new elements in the high-K films was verified and the sensitivity of the SPDI technique for these elements was evaluated. For each element, a bare wafer was prepared with a reference spot A (ethanol) and 3 spots with different concentrations of the elements in the dissolution (X-Chlorides in ethanol). Figure 5 shows the integrated image of one wafer as an example with a clear correlation of the brightness within the spots with the increasing concentration from A to D.

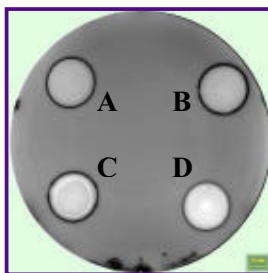


Fig. 5. bare wafer with 4 spots Spot B-D with increasing concentrations, Spot A as reference

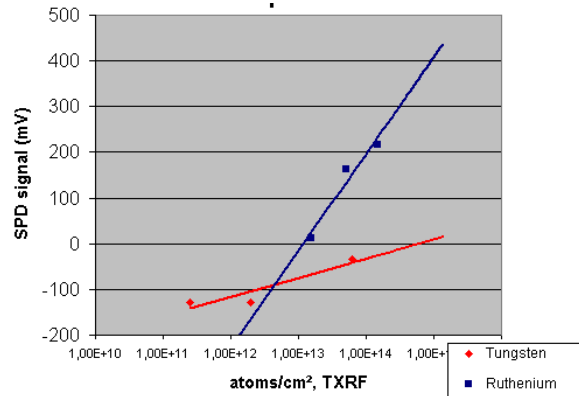


Fig. 6. Correlation of SPD signal to surface concentration as measured using TXRF

For the assessment of the results in Figure 6 we chose the discrete measurement values of the ACM Mode in the spots and for Tungsten and Ruthenium there is a clear correlation between the increasing deposited concentration and the measured SPD signal. The lowest concentration deposited in this experiment, was estimated for Tungsten in the range of 1.6E+11 atoms/cm² and verified with TXRF as 2.47 E+11 atoms/cm².

The SPDI inspection confirmed in principle a very good sensitivity for surface contaminations with Zirconium, Tungsten, Ruthenium and Strontium. To investigate the lowest possible detection limit, further experiments would be necessary. Even the clear identification of the reference spot with the residues of the ethanol warrants further analysis.

In another experiment, backside contamination from the wafer handler system was analyzed. Figure 7 shows the backside of a wafer with typical signatures (arrows) and conspicuous defects (rings). ToF-SIMS analyses were performed at five points for a classification to determine which elements are responsible for the changes in surface potential. At one of the two spots on the ring signature marked with a red circle ToF-SIMS highlighted significant contamination with K, F, C, Fe, Na, Al, and Cu. This example shows the strength of the system for the root cause analyses in contamination monitoring.

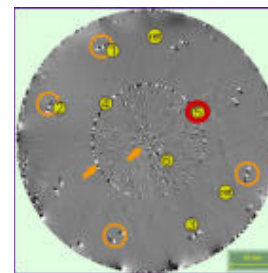


Fig. 7. Correlation of SPD signal to surface concentration as measured by TXRF

V. DETECTION OF ORGANIC CONTAMINATION

The development of new process flows in the backend line for specific packages historically required many specific surface analyses with ToF-SIMS and AES in order to optimize resist strip and cleaning sequences. These analysis requests were an important trigger for the evaluation of the SPDI technique, especially as a pre-scan for finding the most effective path to select the location for analysis with ToF-SIMS or AES.

The ability to perform full wafer inspection for organic contamination was also an important element for this study. With the combination of a scanning surface analysis method and an element analysis at the relevant spots, the analytical lab was able to provide more reliable data for problem descriptions with spatial signatures and better statistics during this evaluation.

Finally, the activities were focused on resist strip sequences and the possible cross contamination of wafers from used FOUPs. Hereby the FOUP cleaner was identified as a source for the contamination.

Examples for the assessment of the resist strip sequences are shown in Figure 8. The clear signature of the wafers with the open fuses and the remaining Al residues (picture A) at the left half side can be seen in every experiment for the root cause analysis. In addition to these signatures from the metallic contamination, the more or less significant remaining organic residues at the wafer center from the resist strip process were clearly detected (the images are showing worst cases from the experiments with variation of process parameters).

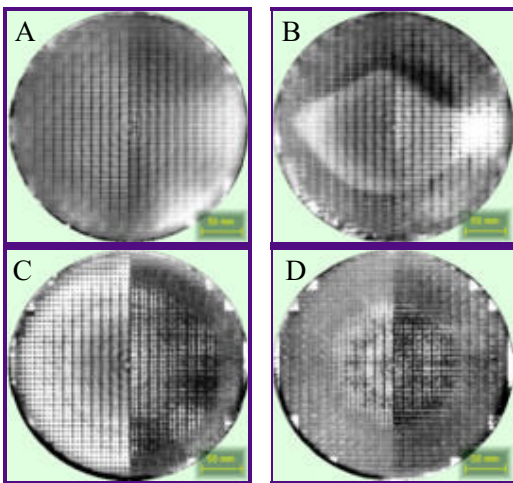


Fig. 8. SPDI signal maps measured with backend wafer
A: reference wafer with 1/2 side open fuses
B: signature from organic contamination post resist strip
C+D: signatures from organic contaminations post wet clean

With the very detailed analysis of the experiments for the backend line, a very good lateral resolution of the SPDI technique has been confirmed. Figure 9 shows a differential

SPD measurement of parts from a die as a reference (left) without residues and a part with organic residues (right). With these known signatures and measurement values, typically requested additional ToF-SIMS analysis for these kinds of experiments can be reduced or avoided and the assessment of the split-experiments can be done with the results from this fast inspection technology.

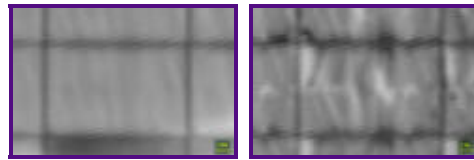


Fig. 9. SPD signal map measured at reference die (left) and one die effected by organic residues (right)

Also, the ACM Images highlight a significant difference in the surface potential for the affected die as shown in Figure 10.

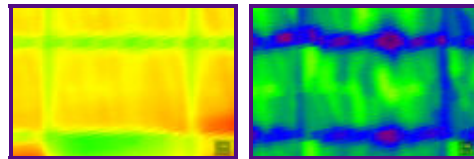


Fig. 10. ACM mode images from the same area with the highest surface potential for the affected die

The transport of silicon wafers in carriers, or FOUPs can be a contamination source for wafers. This is known in the semiconductor industry and mostly identified indirectly with optical wafer inspection. The SPDI technique provided several results as shown in Figure 11. The left image shows contamination of the wafer edge after a long-term transportation in a FOUP. The SPD signal is caused by a kind of polymeric plasticizer typically due to direct contact with synthetic materials and identified with ToF-SIMS analysis.

The wafer gallery on the right side shows increasing organic contamination of incoming wafer material. The wafers in the highest FOUP slots (#22 to 25), with the shortest distance to the plastic walls, exhibit the strongest outgassing signatures.

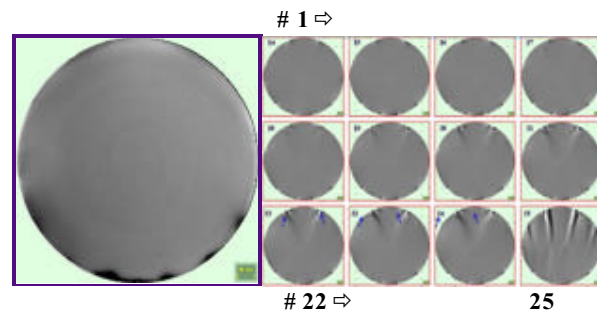


Fig. 11. SPDI images from bare wafer showing organic contamination at wafer edge and highest pos. in a FOUP

VI. DETECTION OF SPD DIFFERENCES

Going back to the Kelvin probe principle, it is obvious that the measurement of the surface potential across the wafer surface is able to provide interesting data as it relates to the surface state of a wafer after processing. Two examples showing the advantage of the SPD measurement are provided below.

The measurement of the wafer SPD as shown in Figure 13 helped identify the root cause for small holes in a copper seed layer. X-ray photoelectron spectroscopy (XPS) confirmed the presence of critical elements at the surface of the conspicuous wafer (blue) for this process issue, and provides a possible method for monitoring this issue in line.

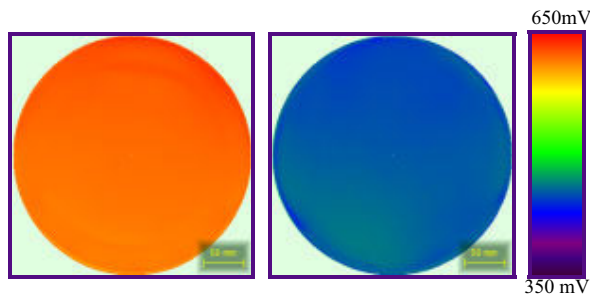


Fig. 13. SPDI images from wafer with thin CVD oxide highlighting SPD differences related to plasma damage

A different experiment was designed to investigate a possible increase in etch chamber contamination between regularly scheduled cleaning cycles. Figure 14 shows consistent SPD measurements of wafers measured before the etch process (top row). SPD measurements made after an etch process shows a clear correlation between SPD values and RF chamber hours. ToF-SIMS analyses on these wafers showed increasing concentration of typical post-etch residues including Chlorine (Cl) and Bromine (Br).

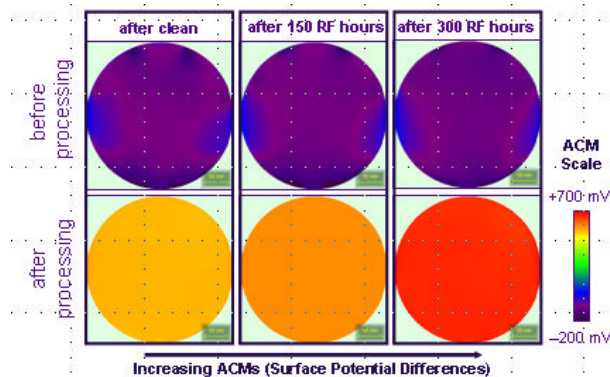


Fig. 14. Correlation between RF hours and SPD values highlight in line monitor for etch chamber contamination control

VII. CONCLUSION

The evaluation of SPDI inspection technology as a detection methodology for thin monolayer NVRs took 6 months. The ChemetriQ inspection system supported at least 10 use cases in different areas of the wafer fab and backend packaging line.

The main advantage of this method for contamination control was the capability to provide fast and reliable inspection of the complete surface of product or bare wafers as a pre-scan for TXRF or ToF-SIMS analysis. NVR defects like organic and metallic residues were detected. It was also demonstrated that SPD measurements can be very helpful for the identification of contamination sources using wafer-to-wafer comparisons.

The SPDI inspection system significantly reduced the time to result in the experiments from this study and also improved the learning rate for process engineering. Additionally, the sensitivity for relevant new elements in high-k deposition and etch processes was very good for setting up effective experiments for contamination control protocols.

In final review of the NVR detection capability assessment in Table 1, the ChemetriQ inspection system has demonstrated its ability to bridge the gap for providing fast detection and spatial signature mapping of monolayer type NVR defects. The ability to use this for pre-scans to localize the defects, especially organic contamination, was very important.

With the experiences out of this study, the tool enables the design of experiments with higher process relevance. In many cases product or test wafers with process simulations were used for the analysis of contaminations instead of simple test wafers with handling sequences.

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