Active Monitoring and Control of Electron Beam Induced Contamination

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ABSTRACT

The vacuum system of all scanning electron microscopes (SEMs), even in the so-called "clean" instruments, have certain hydrocarbon residues that the vacuum pumps do not effectively remove. The cleanliness of the vacuum and the amount and nature of these residual molecules depends on the type of the pumps and also on the samples moved through the system. Many times, the vacuum readings are quite good but the electron beam still leaves disturbing contamination marks on the sample. This means that in a CD-SEM, repeated measurements cannot be done without extra, sometimes unacceptably high measurement errors resulting from "carry-over." During the time necessary for even one measurement, the sample dimension can change, and the extent of this change remains unknown unless a suitable contamination deposition measurement technique is found and regular monitoring is implemented. This paper assesses the problem of contamination of carbonatious materials in the SEM and shows a possible method for its measurement and presents a promising solution to the contamination deposition problem.

Key words: scanning electron microscope, CD, SEM, contamination, measurement, CD-SEM, lithography, metrology, accuracy, linewidth

1.0 INTRODUCTION

The deposition of electron beam induced hydrocarbon contamination is a pervasive problem in scanning electron microscopy. Deposition of contamination on a sample is typically an unwanted and negative effect (although it has been controlled and used positively to manufacture atomic force microscope (AFM) probes). Many times the vacuum readings appear quite good but the electron beam still leaves disturbing contamination marks on the sample. This means that, in a CD-SEM, repeated measurements cannot be done without extra, sometimes unacceptably high measurement errors resulting from "carry-over." Carryover is the increase in dimension size due to the deposition of hydrocarbon contamination deposited by the electron beam on the edges of the structure being measured. The hydrocarbon moieties being deposited are from a variety of sources including the vacuum system, stage lubricants and the sample itself. During the time necessary for even one measurement, the sample may change, and the extent of this change is unknown unless a suitable contamination measurement technique is found and regular monitoring is implemented. In an earlier report, some of the causes of contamination in laboratory scanning electron microscopes (SEMs) were reviewed and potential solutions were presented (Postek, 1996). This work expands upon that earlier study

and provides an additional active monitoring and control approach to solving this problem.

2.0 MATERIALS AND METHODS

Throughout this study a Hitachi2 S-4700 laboratory SEM, a Hitachi S6280-H CD-SEM and an S-806 tilt SEM were used. The two latter instruments were equipped with 150 mm wafer stages. The CD-SEM was equipped with two turbomolecular pumps and two Ebara dry pumps. The tilt SEM had one turbomolecular pump and two rotary pumps. The S-4700 laboratory SEM was equipped with the factory-installed pumps: one diffusion and two rotary mechanical pumps. The samples used in the study were clean wafers or diced chips from wafers made with various processes used in silicon integrated circuit technology. In this study the rate and amount of contamination deposited on these samples were investigated and some of the possible methods of reducing the effects of contamination, including a new anti-contamination apparatus, called Evactron™, were also explored.

2.1 Evactron™. The Evactron[2] is an automatic plasma cleaning and vacuum monitoring system. The system can measure the vacuum level and by the use of valves control the pressure of the gases introduced into the chamber needed for plasma cleaning. It has a built-in power supply to drive a plasma-generating head. Figure 1 shows the schematic diagram of the Evactron cleaning head. The unit is mounted on the wall of the SEM sample chamber and has a controller that can be configured to automatically control the entire cleaning process. The cleaning procedure is performed at much higher pressure (40-100 Pa) than the normal operating pressure (10-3 - 10-4 Pa) of the specimen chamber. The cleaning cycle starts with the closing of the necessary valves to separate the specimen chamber from the electron optics. In the best case, the specimen chamber can be simply separated from the turbo-molecular or diffusion pump. In other cases, depending on the design of the vacuum system the procedure will vary. The next step is to let gas (filtered, clean, room air or oxygen-argon mixture for faster cleaning) into the specimen chamber and stabilize the pressure at its optimal value of 80 Pa. After reaching this point, the high (13.56 MHz) frequency power is applied to the cleaning head for a few minutes. The power applied and time duration depends on the size of the chamber. This procedure provides a gentle plasma cleaning. The nascent oxygen present in the chamber quickly reacts with the residues in the vacuum, and the products are pumped out. To accelerate this step it is advantageous to use a clean N2 flush. In the case of an oxygen - argon gas mixture this step is mandatory. This procedure can easily be made fully automatic, thus the user only has to start the unit and wait until it has finished and the SEM is ready for its regular work schedule.

2 Certain commercial equipment is identified in this report to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose. EVACTRON is a trademark of XEI Scientific.

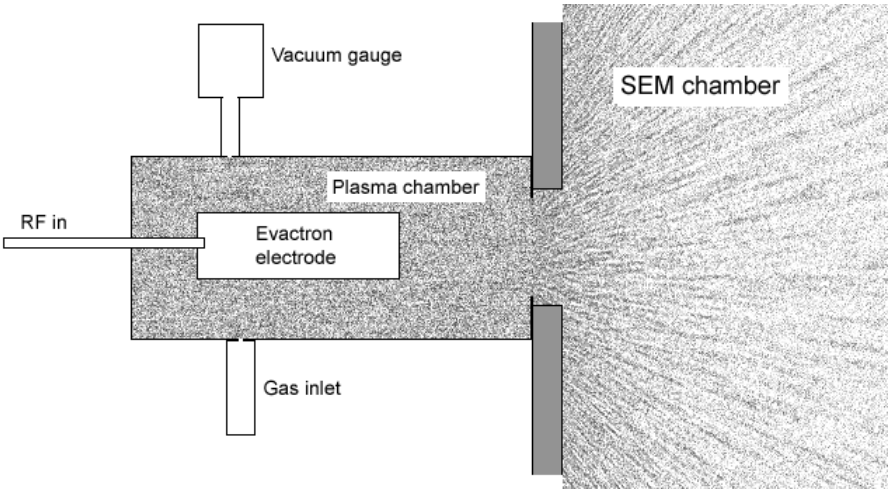

Figure 1. Schematic diagram of the Evactron cleaning head

3.0 RESULTS

Figure 2 illustrates the contamination deposition behavior of two CD-SEMs. Each instrument examined the same UV photoresist wafer. The instruments were programmed to go to a specific isolated line and without moving the sample perform 50 (so-called static repeatability) measurements. While one instrument was able to report the 50 repeated measurements to within less than 2 nm change in the linewidth, the values obtained with the other tool shifted close to 8 nm. Typically, linewidth measurements are done from repeated line scans or averaged images (which exhibit similar behavior). Thus, the deposition of contamination can invalidate the data since an SEM with a severe contamination problem is not capable of measuring the line without changing the width. This may occur even after a single scan. The case of a positive carry-over is especially suspicious, because that may be a sign of serious contamination. Precise measurements require the measurement and understanding of the contamination rate. Without measuring the rate of contamination, which in effect is a measurement error, valid dimensional measurements cannot be done. Furthermore, a thick layer of beam-induced contamination can act as a resist and those locations that were measured with the SEM may not etch at the same rate as similar undisturbed areas during subsequent processing.

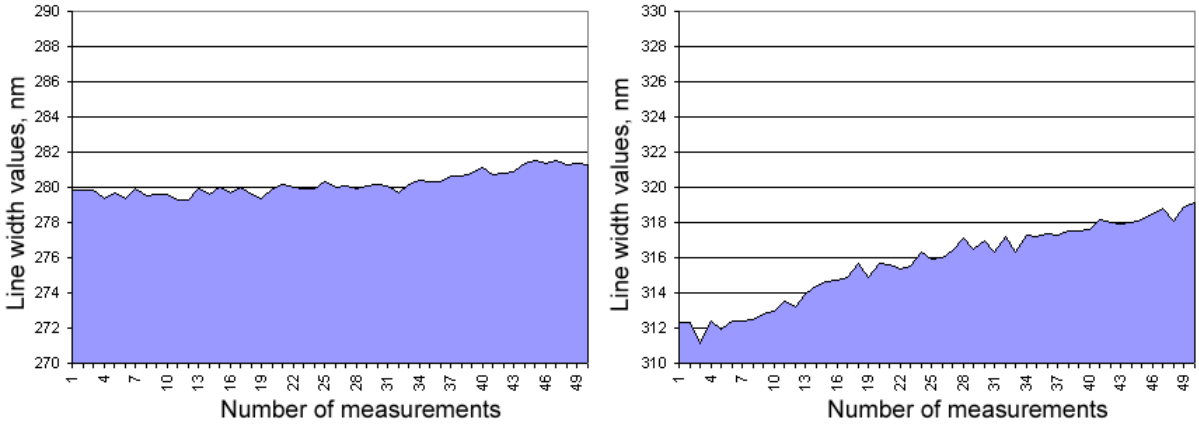

Figure 2. The results of 50 repeated line width measurements with two different CD-SEMs with the same UV photoresist wafer.

It is suspected that the contamination layer formed by the electron beam comes from two sources: the vacuum and the sample surface. Reimer (1993) describes a process of drift of large molecular weight molecules under the electron bombardment. The deposition of the contamination layer is a dynamic process. Molecules arrive at and leave the sample surface at the same time. The amount of contamination deposited depends on the electron dose, (i.e. the length of time the beam dwells on the sample). The longer the dwell time, the thicker the contamination becomes. Figure 3 and Figure 4 illustrate this process. In the case of Figure 3, the (5 kV, 10 pA) electron beam was left on a clean, etched silicon sample for two hours at high magnification. Viewed at lower magnification, the very heavy deposition of contamination is formed as a "sculpture" with a peak at the upper left corner. The electron beam created the frame of the structure because it dwelled longer at the edges before the sync pulses arrived and initiated the horizontal and frame scans. Furthermore, just before the frame scan began the electron beam dwelled a bit more at the upper left corner, therefore the beam remained stationary at that point for the longest time overall and formed a somewhat taller contamination peak (not unlike an e-beam deposited AFM probe). The structure appears distorted because the beam and/or the sample stage drifted during the long irradiation time. The presence of the vertical line (originally the left edge of the frame) near the middle of the contamination-induced frame clearly proves that once contamination has been deposited, the electron beam cannot remove it. If viewed in real time at high magnification, the operator does not readily see the contamination. The image that is displayed on the viewing screen is about 20% smaller than this frame hence, the electron beam typically over-scans a larger area on the sample than the electron beam displays on the screen. Therefore, the most disturbing part of the contamination deposited at high magnification is that the effect of contamination is typically not observed by the operator except when going back to lower magnifications.

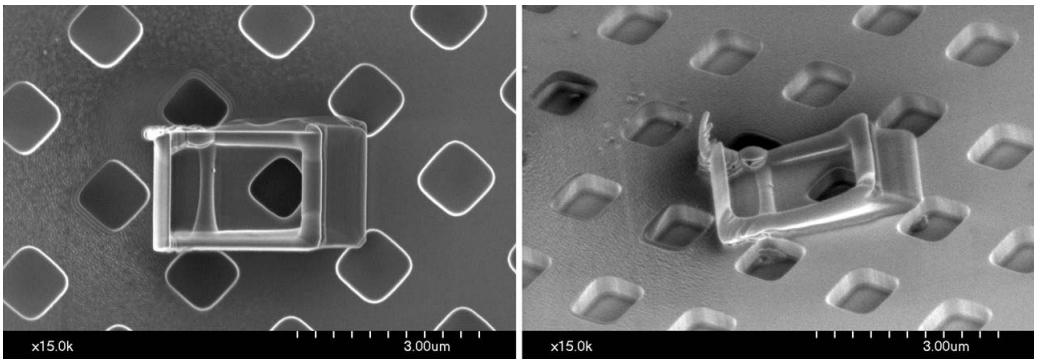

Figure 3. Contamination formed on a silicon wafer sample during 2 hours of continuous electron beam bombardment. The left image was taken with 60° sample tilt and the 3-dimensional structure of the contamination can be observed.

Figure 4 shows an etched silicon "grass" sample at 50 000 times magnification. This sample was bombarded with a 5 kV, 10 pA electron beam at 500 000 times magnification. The area shown on the screen of the SEM at this magnification is marked close to the center of the image. The 500 000 times magnification image is inserted at the lower right corner. The typical frame-like contamination mark is not visible any longer; the dynamic process formed only a circle at this very high magnification. The electron beam was left on the sample for 10 minutes.

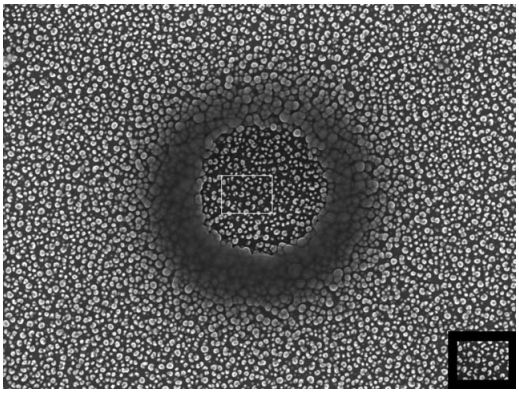

Figure 4. Etched silicon "grass" sample at 50 000 times magnification, which was bombarded with a 5 kV, 10 pA electron beam at 500 000 times magnification

Figure 5 shows two images taken with CD-SEM. In this case, the (800 V, 3 pA) electron beam bombarded the sample for 6 minutes. During this time the sample/beam drift and the contamination resulted in the enlargement of the corner section by about 0.15 micrometer. Similar effects can take place in shorter times, in severe cases even in a few seconds.

The extent that deposited contamination contributes to measurement errors in CD-SEMs will remain unknown unless the operator is aware of this problem and regular correct examinations and measurement of the contamination rate is conducted.

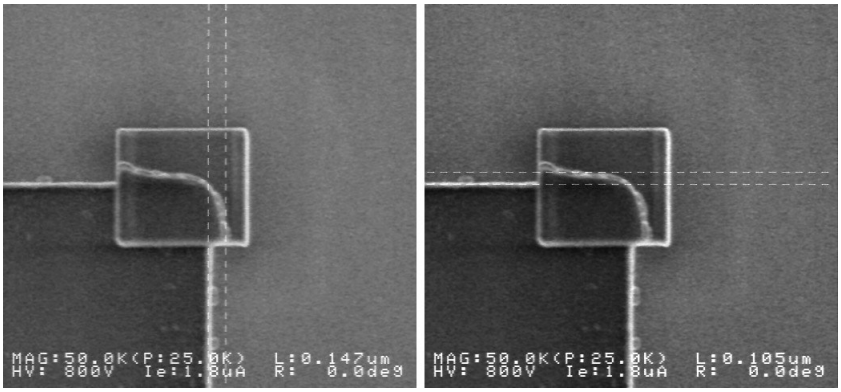

Figure 5. X and Y enlargement of the corner region due to contamination and drift in a CD-SEM. 800 V, 3 pA electron beam bombardment for 6 minutes.

3.1 Anti-contamination Devices. Clearly, electron beam induced contamination is a real problem in scanning electron microscopy and no instrument is totally free of this problem. Even dry pumped instruments can deposit contamination (generally at a much lower rate). Contamination also results from hydrocarbons brought into the proximity of the electron beam by the specimen itself. Regular contamination rate measurements may reveal the extent of the problem, but if the errors due to contamination are too high, something has to be done to lessen the problem. One possibility with certain SEMs is the use of a liquid nitrogen anti-contamination device. An anti-contamination device is essentially a small, flat metal piece located above the sample surface that is kept at liquid nitrogen temperatures. The anti-contamination device, by working essentially as a getter pump or cold trap, collects the good part of the contaminants. Therefore, the localized sample contamination rate, at the sample, is reduced. It should be noted however, that once the device is allowed to warm-up the trapped contaminants are released. Figure 6 shows an etched silicon "grass" sample viewed at 50 000 times magnification in an instrument equipped with a liquid nitrogen anti-contamination device. This sample was bombarded two times at two different locations at 100 000 times magnification for 10 minutes (@ 5 kV, 10 pA). The left image of Figure 6 was collected without liquid nitrogen added to the device, and the right image was taken with the same conditions but with the anti-contamination device fully charged with liquid nitrogen. The amount of contamination is certainly reduced, but it is still remains high.

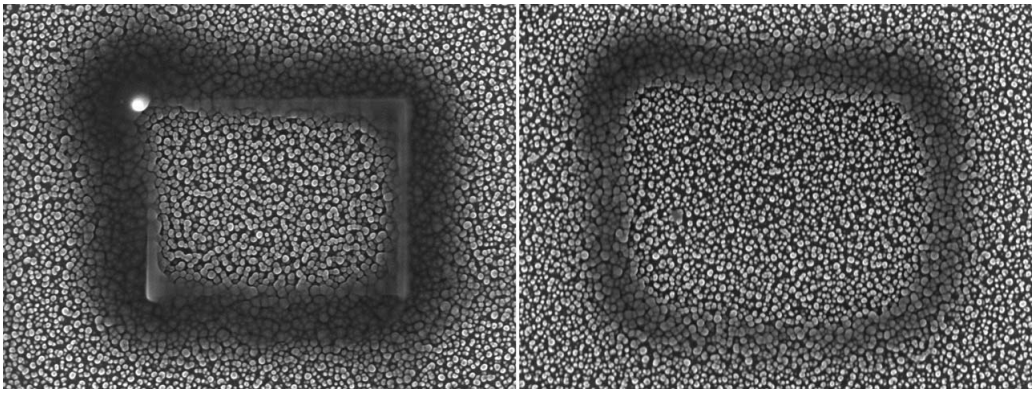

Figure 6. Two locations of a silicon "grass" sample irradiated for 10 minutes without (left) and with (right) the application of liquid N2 to cool the anti-contamination device (50 000x).

3.2 Evactron Cleaning. Figure 7 shows two images of the same silicon "grass" sample viewed in the same scanning electron microscope as Figure 6. For the purposes of easy comparison, the left image is the same as the image on the left of Figure 6 but the right image was taken after the Evactron unit was turned on and the cleaning procedure applied for ten minutes. On the right side of Figure 7, where the Evactron anti-contamination device was used, the amount of contamination is greatly reduced. The amount deposited is also far less than even with the liquid nitrogen-cooled anti-contamination device.

The SEM that was used to take the images in Figure 7 was a cold field emission gun instrument. It was equipped with a liquid nitrogen cold trap above the water-cooled baffle on top of the diffusion pump. This instrument was also equipped with a gaseous nitrogen

leak system where needle valves in the fore lines of the mechanical pumps are set to about 2 Pa. This intentionally inhibits the rotary pumps from reaching their ultimate vacuum (Postek, 1996). This leak is small enough keep the pump efficiently backing the diffusion pump or pump-down the specimen exchange chamber with no compromise to the ultimate chamber vacuum. But, the continuously streaming of nitrogen molecules into the line minimizes the potential of backstreaming of oil from the rotary pumps. This simple system provides an effective mechanism for reducing instrument-induced contamination but in many cases , as shown here, may not be sufficient.

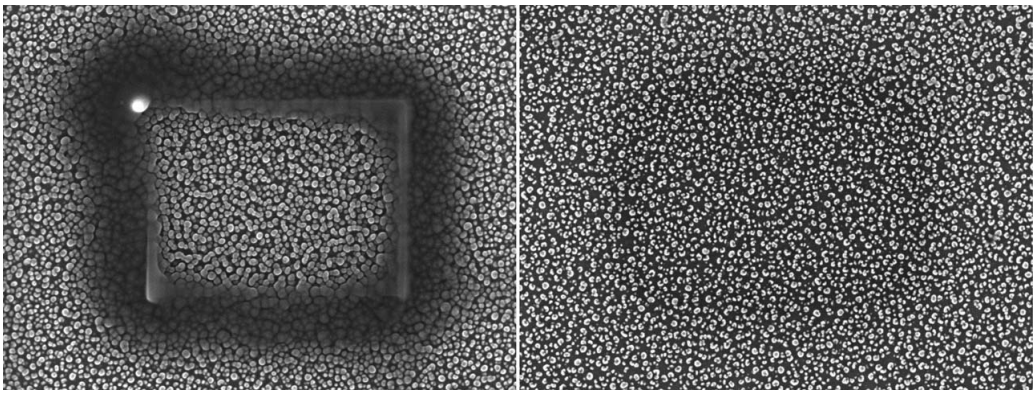

Figure 7. Two locations of a silicon "grass" sample irradiated for 10 minutes before (left) and after (right) the use of Evactron anti-contamination device. 50 000x

CD-SEMs are typically equipped with turbomolecular pumps and oil-free fore line pumps to provide better, cleaner vacuum. Even with these pumps, many SEMs are not clean enough and disturbing contamination deposition occurs. Regular monitoring and if necessary, instrument cleaning has to take place. For monitoring two possible ways can be followed: 1) measure the rate of contamination with the Evactron, which shows the cleanliness of the vacuum, or 2) measure the effect on dimensional measurement by measuring the change occurring during repeated measurements. The rate measurement is more advantageous in general, but it may

not be as applicable for all samples. This is because different samples made of different materials are prone to contaminate at different rates and the samples themselves are sources of the contaminating molecules as well. Another possibility for sample dimensional change that must be recognized is that the sample under test can become distorted by the electron beam exposure itself (Postek et al., 1989). So, the distinction between change due to contribution from contamination deposition and electron beam induced change must be properly assessed.

After several Evactron treatments, the vacuum begins to stay clean for longer periods of time and the frequency of necessary Evactron treatments becomes less. Nevertheless, since the cleanliness of the vacuum depends also on the nature and cleanliness of samples going through the system, regular monitoring of the contamination rate can indicate when another cleaning cycle must take place. Figure 8 shows an image taken with a tilt wafer SEM. Prior to the Evactron cleaning, it was impossible to work without severely contaminating the sample. The instrument underwent a series of 10-minute Evactron cleanings. After the cleanings, only a small amount of contamination developed under the electron beam. This is illustrated by the light contamination mark on the clean, freshly etched polysilicon sample.

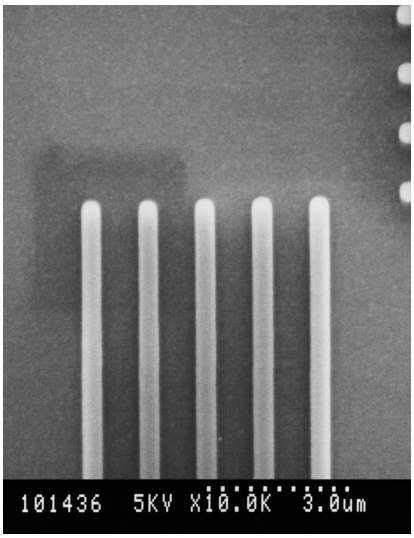

Figure 8. Tilt wafer SEM. Minimal contamination mark on a polysilicon sample after treatment, 15 minutes dwell time at 30 000x magnification, @5 kV.

3.3 Sample Cleaning. Once contamination has been deposited on a sample it is possible to remove it to some extent with in situ oxygen plasma cleaning using the Evactron. Figure 9 illustrates this cleaning procedure on a silicon "grass" sample. Both of two locations of the sample were irradiated for 10 minutes. The left image of Figure 9 is the untreated sample. The image on the right of Figure 9 was taken after a 60-minute treatment of the sample with the Evactron anti-contamination device. It is important to point out that long treatment of the sample may also alter the "clean" areas as well.

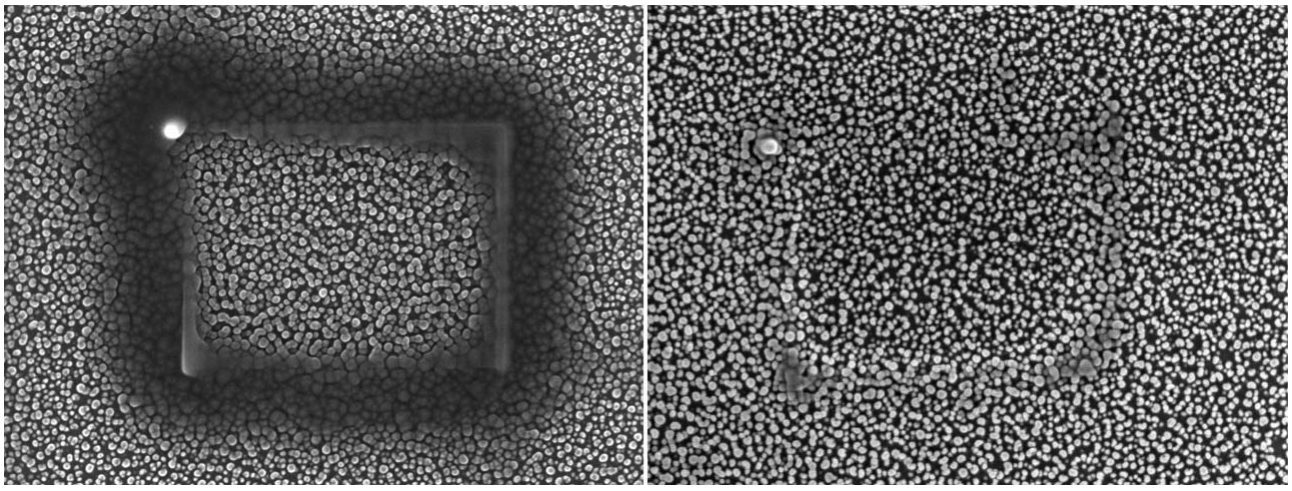

Figure 9. Silicon grass sample that was irradiated for 10 minutes. The left image was taken after contamination deposition and is shown untreated. The image on the right was taken after a 60-minute in-situ treatment of the sample with Evactron anti-contamination device. 50 000x

4.0 CONCLUSIONS

Contamination of various samples under the electron beam has been demonstrated to cause measurement errors in laboratory and CD-SEMs. The extent of the error is unknown unless regular monitoring of the contamination rate is implemented. Depending on the severity of the problem, removal of the contaminating molecules must take place. This paper described a new cleaning method using an active plasma system that was found to be effective in cleaning the vacuum of the specimen chamber of laboratory, and production metrology SEMs.

5.0 ACKNOWLEDGEMENTS

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6.0 References

Postek, M. T. 1996. An approach to the reduction of hydrocarbon contamination in the SEM. SCANNING 18:269-274

Postek, M. T. 1989. Scanning Electron Microscope-based Metrological Electron Microscope System and New Prototype SEM Magnification Standard. Scanning Microscopy 3(4):1087-1099

Reimer, L.: Image Formation in Low-Voltage Electron Microscopy SPIE Opt. Eng. Press; Volume TT 12 (1993) ISBN 0-8194-1206-6