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Improvements of Secondary Electron Imaging and Endpoint Detection in Focused Ion Beam Circuit Modification

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Abstract

Secondary electron signal is widely used in Focused Ion Beam (FIB) systems for imaging and endpointing. In the application of integrated circuit modification, technology has progressed towards smaller dimensions and higher aspect ratios. Therefore, FIB based circuit modification processes require the use of primary ion beam currents below 10 pA and Gas Assisted Etching (GAE). At low beam currents, short pixel dwell times and high aspect ratios, the level of available secondary electrons for detection has declined significantly.

FIB GAE and deposition requires delivery and release of a gaseous agent near the beam scanning area, and involves insertion of a gas delivery nozzle made of conductive material and grounded for charge prevention purposes. The proximity of a grounded gas delivery nozzle to the area being milled and/or imaged creates a "shielding" effect, further lowering secondary electron signal level.

The application of a small positive bias to the gas delivery nozzle provides an effective way of reducing the "shielding" effect. Depending on the geometrical arrangement of the gas delivery system and other conductive objects in the chamber, an optimized nozzle bias potential can create conditions favorable for enhanced extraction and collection of secondary electrons.

The level of the secondary electron image signal, collected in an FEI Vectra 986+ system, from a grounded copper sample with the nozzle extended and biased can be enhanced as much as six times as compared to the grounded nozzle.

Secondary electron intensity endpoint is improved on backside samples, however shielding of the nozzle field by the bulk silicon substrate limits the electron extraction effect from within a via. For front side edits the improvement of endpoint signal level can be dramatic.

Lateral image offset induced by the electrostatic field of a biased nozzle, can be removed by software position compensation.

Introduction

For over a decade, FIB Circuit Edit (CE) has been a powerful tool for design evaluation and debug of integrated circuits. A typical FIB CE system configuration includes a vacuum chamber with a FIB column installed on the top of the chamber and a Micro Channel Plate (MCP) detector attached to the bottom of the column facing the sample. The sample is positioned in the chamber a few millimeters from the MCP detector and grounded to reduce charge buildup.

In CE GAE and material deposition from a gaseous precursor are commonly used. These processes require relatively high local pressures of the process gas in the edit area. In order to create this high local pressure, a gas delivery nozzle is brought near (about 100μm) to the point of interaction between the ion beam and the sample. The nozzle is typically made out of conductive material and grounded to the chamber in order to reduce charge buildup.

The IC trend towards smaller features has caused an increase in the aspect ratio of the vias that must be milled to access and rewire the circuit. In addition, low ion beam currents are used for the via milling further contributing to decline of the secondary electron signal level available for imaging and endpoint detection during FIB circuit editing. Insertion of a grounded gas delivery nozzle into the space between the MCP detector and the sample further reduces the level of secondary electron signal. The introduction of the GAE nozzle near the milling area noticeably reduces the Signal to Noise (S/N) ratio of secondary electron images taken at low beam currents and provided the impetus for this study.

To reduce the side effects the presence of the gas delivery nozzle causes, previous studies proposed applying a negative bias to the nozzle in order to improve the secondary ion collection efficiency in a Secondary Ion Mass Spectrometer (SIMS) apparatus [1], but we are not aware of any similar work that has been conducted in an FIB system. Application of the negative bias to the gas delivery nozzle in the FIB would be a straight-forward extension of the previous SIMS related invention, but was not studied experimentally as part of this work. We are introducing instead the idea of using a positive bias, applied to the gas delivery nozzle in a CE FIB apparatus to improve secondary electron collection efficiency.

Secondary electron signal collection

When a FIB system is configured for secondary electron imaging, a grid in front of the MCP detector is biased positively (Fig. 1) in order to attract the secondary electrons to the detector.

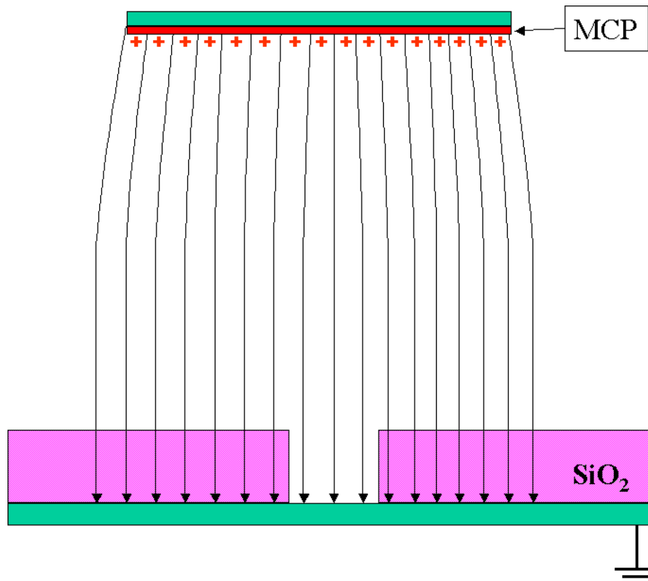

Fig. 1: Secondary electron collection field created by a positive electrostatic potential in front of the MCP detector in an FIB system. The field penetrates through dielectric of the front side sample and terminates on grounded objects beneath the dielectric.

Without a gas delivery nozzle present between the MCP and the sample, the collection field terminates on the sample. In the case of a front side sample, the field penetrates the top layer dielectric and terminates on grounded metal lines. In the case of a backside sample, the field terminates in the grounded bulk silicon.

When a grounded gas delivery nozzle is inserted between the MCP and the sample (Fig. 2), its presence disturbs the collection field created by the grid in front of the MCP. This field partially terminates on the nozzle and the area being milled becomes partially shielded by the nozzle.

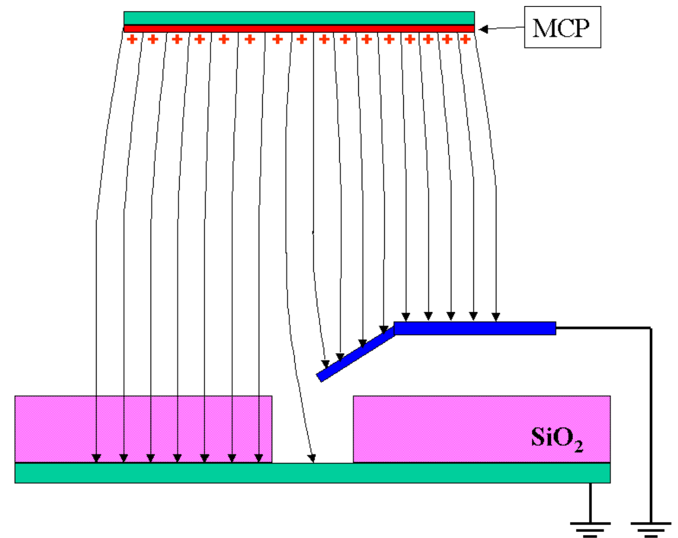

Fig. 2: The secondary electron collection field, created by positive electrostatic potential on the MCP detector in an FIB system, is distorted by insertion of grounded gas delivery nozzle. The strength of the field at the surface of the sample is reduced in the proximity of the nozzle.

The net result of introducing a grounded nozzle into the field of this system is a reduction in the number of secondary electrons collected by the MCP. This decline results in a secondary electron image and endpoint level reduction. The interference of the grounded nozzle can be eliminated by the application of a positive electrostatic bias to the nozzle. Careful selection of the nozzle bias can balance the fields in such a way that the nozzle no longer interferes with secondary electron collection (Fig. 3).

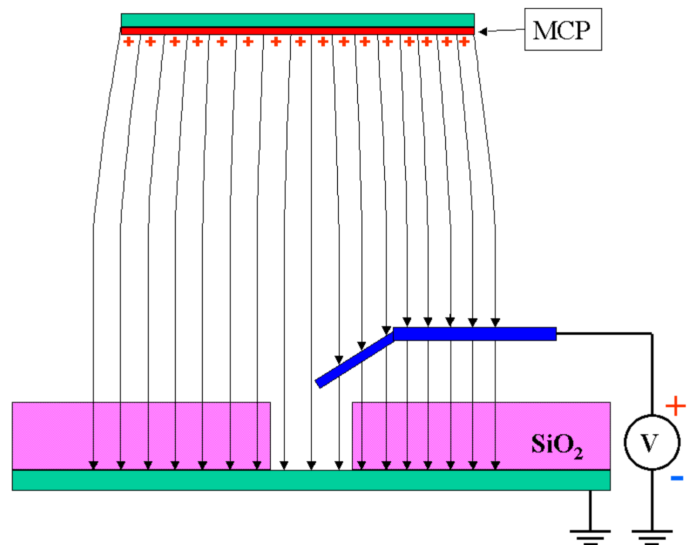

Fig. 3: Distortion of the secondary electron collection field can be significantly reduced by careful application of a positive bias potential to the gas delivery nozzle.

Further increase of the positive potential applied to the nozzle (Fig. 4) increases the strength of the positive electrostatic field at the surface of the sample. As the strength of the field increases, collection of the secondary electrons is also expected to improve. However, above a certain nozzle potential collection efficiency starts to decline. This decline is expected due to the capture of secondary electrons by the strong positive field on the GAE nozzle instead of guiding them to the MCP detector. Additionally, excessively strong electric potentials on the nozzle and drastic changes of electric fields in the system can affect the primarily ion beam in undesirable ways.

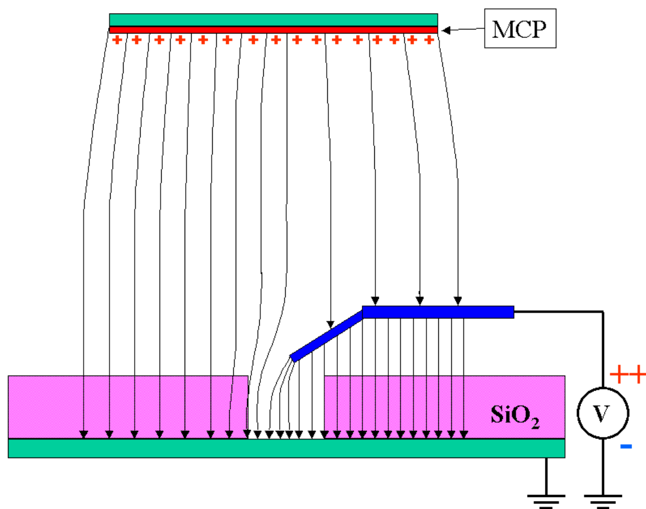

Fig. 4: Further increase of a positive bias potential, applied to the gas delivery nozzle, will enhance the strength of the electrostatic extraction field at the surface of the sample near the nozzle and promote extraction of secondary electrons from the surface. Penetration of the extraction field through the dielectric should promote extraction of secondary electrons from the bottom of via and enhance endpoint detection during front side circuit editing.

Insertion of the gas delivery nozzle in the circular MCP field creates a lateral gradient in the field and causes the ion beam to shift position. The magnitude of the shift is expected to be larger in the case of a positively biased nozzle versus a grounded nozzle. Since the shift is caused primarily by the interaction between the electrostatic fields of the MCP and the nozzle, we expect the direction and magnitude of the shift to be repeatable.

Via milling endpoint considerations

There are two approaches to the modification of integrated circuits: front side and backside.

In the case of front side editing the circuit is accessed through a dielectric while the substrate of the chip is grounded. In this arrangement the electrostatic field, created by the positively biased front face of MCP and/or positively biased gas delivery nozzle, will penetrate through the dielectric (**Fig. 4**) and terminate on the conductors of the integrated circuit. Since the collection field will be present in the bulk of the dielectric, it should assist with the extraction of secondary electrons from the bottom of a via while it is being milled into the dielectric. As a via milled in dielectric reaches metal, improved extraction of secondary electrons is expected and therefore a stronger endpoint signal is also expected.

In backside circuit editing, the circuit is accessed through the substrate of the circuit (Fig. 5). The substrate is sufficiently conductive to shield the electrostatic field and therefore, the field created by the positively biased front face of the MCP and gas delivery nozzle terminates on the substrate itself.

Penetration of the extraction field into a via milled in bulk silicon will be limited and therefore enhancement of the via endpoint detection on a backside sample is expected only due the improved collection efficiency and not due to changing fields at the bottom of a via.

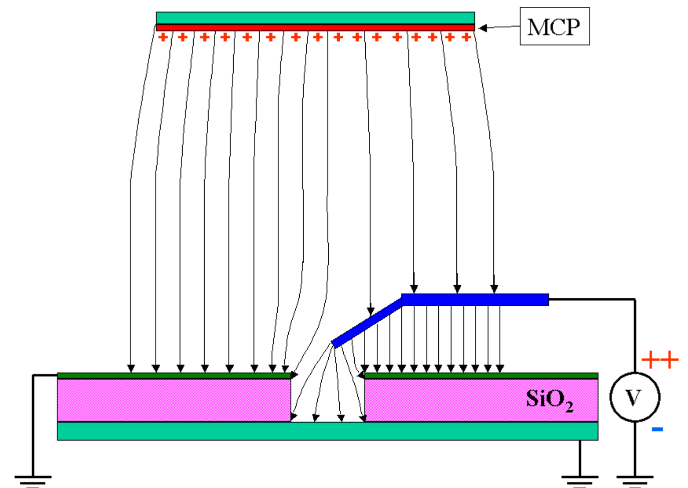

Fig. 5: In the case of backside editing the electrostatic field terminates at the surface of the silicon substrate and does not penetrate into the bulk of the sample. While collection of secondary electrons escaping the via is improved with a nozzle bias, extraction of electrons from the bottom of the via is expected to be less enhanced than in the case of milling through dielectric.

Experimental verification

Series of images were collected for different nozzle conditions and front side via endpointing experiments were conducted on an FEI Vectra 986+ CE system. The results were verified in a more advanced system (VectraVision). Vectra systems are typically equipped with a "penta" nozzle and a high gas flux "beehive" nozzle, both of which when extended noticeably

reduce the contrast of the FIB image. The effect on the image quality is especially strong on the images taken by small beam currents (5pA and below).

In our study, we applied a range of potentials (positive relative to the chamber and stage) to the gas delivery nozzle and we varied the bias on the MCP screen. Imaging experiments were done on a well-grounded copper grid that is used as a Faraday cup in the Vectra system. Lateral image offset, induced by the nozzle bias, was corrected by adjusting the position before image collection.

Endpointing in a via was studied by milling a 0.5 x 0.5µm via in a test sample composed of a 5µm thick dielectric layer over a grounded metal plane.

Results and discussion

Application of a bias as small as +20V to the extended penta-nozzle gas delivery assembly resulted in a considerable increase in the level of collected secondary electron signal (Fig. 6) over no bias. From comparison of images we can see that while the overall brightness of the right image on Fig. 6 is significantly higher than the brightness of the left image on the same figure, areas with the black level of contrast are still present on the bright image. The presence of the black contrast level on the image collected under the biased nozzle conditions indicates that application of the bias does not change the dark level offset of the image and therefore we chose a mean grayscale level of the image as an indicator of the signal level.

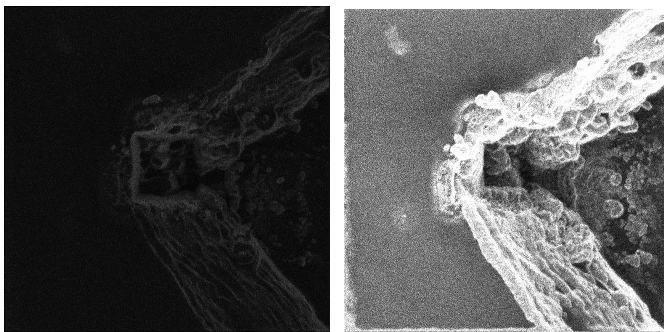

Fig. 6: Grounded Cu sample, FOV10 image with extended "Penta" GAE nozzle, while the nozzle is grounded (left) and biased positively (right), taken under the same, other the nozzle bias, imaging conditions.

A plot of the mean grayscale level for a series of images taken from the same area on the grounded copper grid under various nozzle bias potentials (Fig. 7) shows that it is possible to achieve a five-fold improvement in the image signal level by applying a positive bias to the nozzle of a Vectra system.

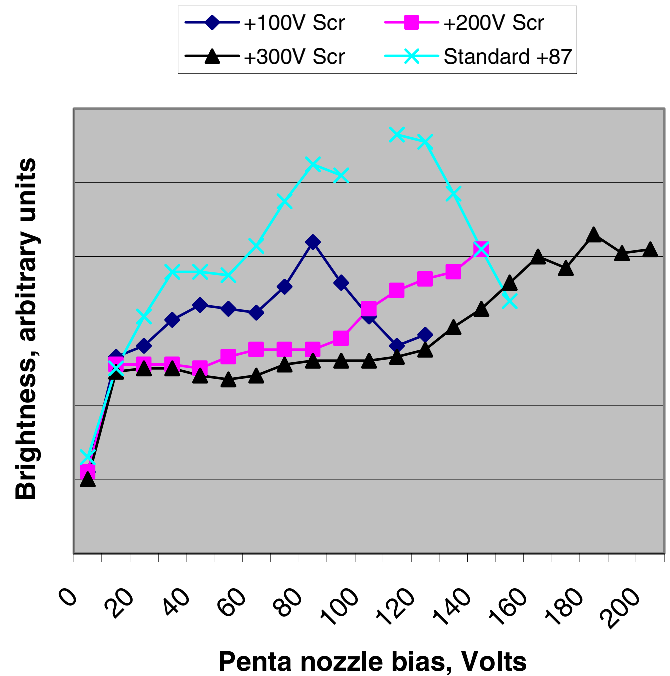

Fig. 7: Level of secondary electron signal, as indicated by mean brightness level on images collected under various MCP screen potential conditions, while varying the positive bias potential on an extended Penta GAE nozzle.

Insertion of a high gas flux delivery nozzle (beehive shape) reduces signal level of the secondary electron image to an even greater level than the insertion of the "penta" nozzle. This nozzle is specifically designed for super-enhanced GAE such as the removal of bulk silicon in backside editing and therefore is not used for fine line imaging and milling. A positive bias, applied to the "beehive" nozzle, has a focusing effect on secondary electrons emitted from the sample and helps to form a useful (Fig. 8) secondary electron image.

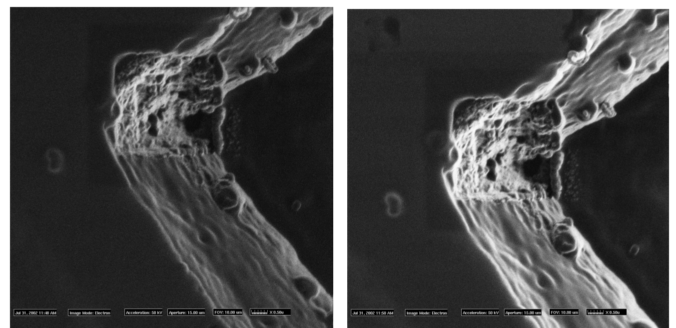

Fig. 8: Grounded Cu sample, FOV10 image with extended "Beehive" GAE nozzle, while the nozzle is grounded (left) and biased positively (fight), taken under the same, other then the nozzle potential, imaging conditions.

It is possible to improve the signal level of secondary electron collection through the "beehive" nozzle by as much as a factor of eight (Fig. 9).

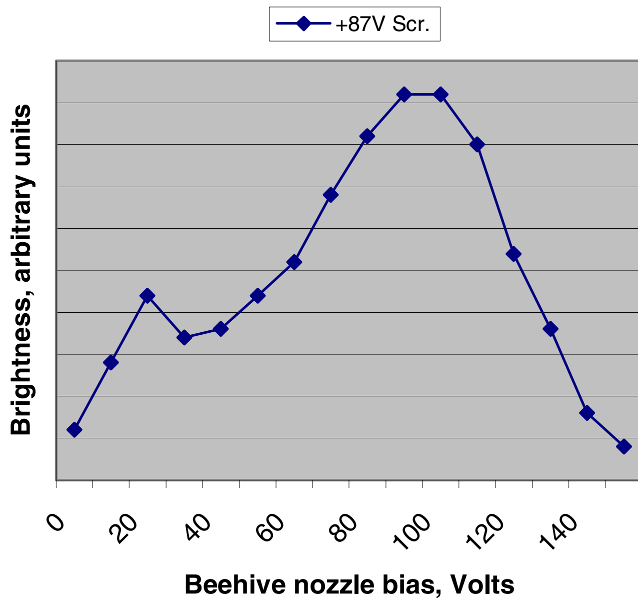

Fig. 9: Level of secondary electron signal, as indicated by mean grayscale level on images collected under +87V MCP screen potential conditions, while varying positive bias potential on extended "Beehive" GAE nozzle.

We verified experimentally the prediction that during via milling, endpoint to metal through a dielectric is enhanced when the nozzle is positively biased. While milling a via that is 0.5 x 0.5µm and 5µm deep, the endpoint signal is greatly enhanced when a positive bias is applied to the "penta" nozzle (Fig. 10), comparatively to the grounded nozzle situation.

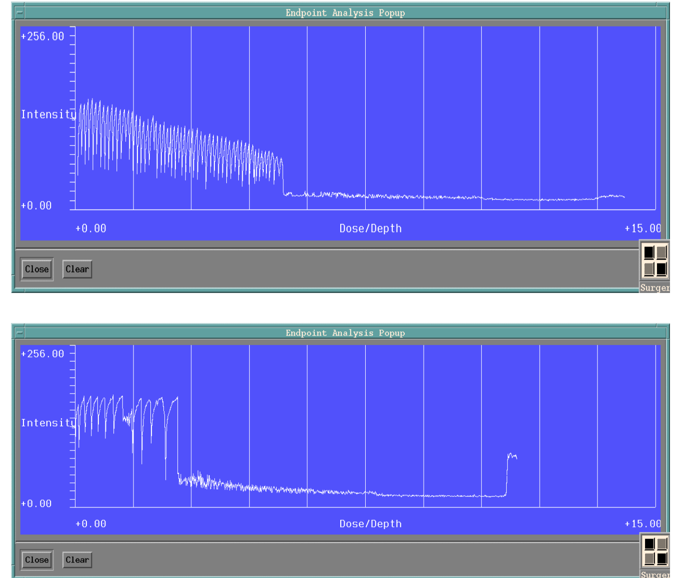

Fig. 10: Vectra 986+ secondary electron intensity endpoint plot for a 0.5µm x 0.5µm via with 10:1 aspect ratio, milled through dielectric using a GAE process with the gas delivery nozzle grounded (top) and biased positively in relation to the sample (bottom).

Conclusion

We have introduced the idea of treating the gas delivery nozzle of an FIB system as a component of the electron optics system and that by appropriately biasing it we can improve secondary electron signal collection and endpoint detection. Experimental results have confirmed our theory and we have measured improvements as much as eight-fold in some cases. This approach is extendable to the more general concept of placing the secondary particle collection electrode as close to a charged particle beam to sample interaction area as possible. This concept could be applicable not only to FIB systems with in-situ reactive gas etching, but also to any scanning focused particle beam tool, particularly Scanning Electron Microscope (SEM) and to SEM-like systems, either with or without gas delivery components for in-situ reactive gas etching.

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References

1. R. Gerlach, L. Christman, and M. Utlaut, U.S. Patent 6,414,307