FIB & TEM Application Methods with Related Theory Explanations

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Abstract*- As a key part of failure analysis function in semiconductor foundry industry, TEM micro-topography becomes more and more important while semiconductor devices' critical dimensions get smaller and smaller. And the FIB/TEM sample preparation technique takes the first priority to achieve high quality TEM pictures. Normally FIB operators have to avoid sample defects such as sample bending, poor thickness uniformity, excessive amorphization, sample contamination etc. with necessary FIB manipulation skills for FIB/TEM sample quality control. In this article, the author will introduce a couple of theories to explain how FIB beam acts on sample surface and provide several FIB milling tricks to hedge sample defects. The theories and tricks include FIB beam energy's Gaussian distribution, FIB beam spot's asymmetric deformity and some reasonable FIB milling approaches to protect TEM sample from deforming etc., which will be illustrated in this article. And all of the application theories and skills are described based on dual beam FIB equipment system.

I. INTRODUCTION

FIB means Focused Ion Beam which uses liquid metal gallium as ion source for micro-scale incising under electric field with generally 30kV acceleration voltage. As a mature equipment type in the years from 2000 to 2010, dual beam FIB has been widely used for TEM sample preparation in semiconductor failure analysis laboratories. And the commonest application mode of dual beam FIB is cross section milling. Fig. 1 simply describes the cross-section working mode of FIB tools for TEM sample preparation.

II. THEORETICAL MODEL

FIB beam spot's patterning mode and physical form: It is the working mode of FIB patterning incision as the illustration in Fig. 2. Each circle represents a beam spot in Fig. 2. Generally it is an approach of line scan with specified spot overlap rate and spot dwell time. An ideal uniform FIB beam stream in the left of Fig. 3 never exists in real world. In real FIB beam stream, positive charged ions interacts with each other in all 3 dimensions of X, Y and Z. This is called Boersch Effect. And as a result of Boersch Effect, beam stream becomes non-uniform in three-dimensional space. In the right of Fig. 4, it is a simulated top-view image of best-aligned real FIB beam spot in X and Y dimensions. And Fig. 5 illustrates the gradual change tendency of different beam currents' spot energy density distribution. Deeper dark stands for higher energy density. Basically bigger pA current beam has higher energy density in central zone and more dispersive energy distribution in peripheral zone.

FIB cutting shape with Gaussian energy distribution: FIB beam spot's energy distribution is actually a kind of Gaussian distribution as the graphic indication in Fig. 6. Because of the negative impact coming from FIB beam spot's energy Gaussian distribution, trapezoid TEM flake samples will be achieved instead of rectangular TEM lamina samples under precisely perpendicular FIB milling angles with simplex 52° stage tilt as the sketch presents in Fig. 6. The poor thickness uniformity of trapezoid sample will jeopardize sample's imaging quality under TEM camera, and it may cause following issues such as bad TEM diffraction achievement and double images in sample's middle and bottom areas etc.

III. APPLICATION METHOD AND EXPLANATION

Non-orthogonal FIB cut and trick to prevent sample bending: To overcome the problem of trapezoid TEM sample based on FIB beam spot's energy Gaussian distribution, amended stage tilt angles are suggested to perform non-orthogonal FIB cut. For instance in Fig. 7, 53°(or a little bigger/smaller angle depends on real case) stage tilt is suggested for front side cut and 51°(or a little bigger/smaller angle depends on real case) stage tilt is suggested for back side cut. So after all, as every certified FIB operator knows, the 1st trick of non-orthogonal milling method in the right of Fig. 7 is the most vital sense for FIB cross section cut. And somehow the most frequently-occurring defect in FIB/TEM sample preparation is sample bending. It is impossible to place a bent sample's most structures in confocal plane under TEM camera as Fig. 8 shows. And moreover, sample bending usually causes ugly black stripes in TEM image. How does a bent TEM sample come out usually? Most inexperienced FIB operators prefer to choose equal slicing width for both front slicing and back slicing as Fig. 9. When a processing sample is still thick, the structure strength is strong enough to sustain straight sample despite of material stress. Along with the back slicing, the sample gets thinner and thinner. Once the sample becomes thin enough normally under 150nm, the adjacent stress inflection points in same side will get very close to each other. At this instant, the structure strength is not strong enough to confront material stress, and this will easily lead to sample bending. So the 2nd trick is to set different final slicing width for front slicing and back slicing as Fig. 10. In this way, the adjacent stress inflection points in same side could still stay far enough from each other when the sample gets thin enough below critical thickness. And this method could be much helpful to mitigate the impact coming from material stress to keep sample straight.

Mitigating sample amorphization with appropriate FIB beam current: To eliminate double imaging phenomenon under TEM camera, generally FIB operator expects to make sample as thin as possible. But the trap is that it is easy to lead TEM sample to lose whole crystalline silicon layer when sample thickness approach less than 150nm. Without crystalline silicon layer, a TEM sample can't get eligible TEM diffraction contract, and this means poor TEM image quality in middle and high magnification imaging modes. As Fig. 11 illustrates, the damage mechanism is that FIB beam stream transforms the outside crystalline layers into amorphous layers based on FIB beam spot's energy Gaussian distribution. And bigger beam current makes bigger damage. So the trick 3 is that FIB operator is advised to choose FIB beam current as small as possible for final slicing to better keep TEM sample from being amorphous in the pre-condition of that the beam current is big enough to meet the requirements of acceptable slicing speed and no sample bending.

Identifying FIB beam aberration: Like other electronic devices, FIB beam also has its own deterioration mechanism. As Fig. 12 shows, a well-aligned FIB beam spot projects a round circle with a concentric halo while a deteriorated one probably projects an oval circle with an eccentric halo. And this theory could be proved by the burned marks which were created by FIB standing beam spots (not by scanning beam) in the pictures of Fig. 13 and Fig. 14. After all the final result is that good FIB beam performs equivalent slicing effect from left to right while aberrated FIB beam performs asymmetrical slicing effect on left side and right side as Fig. 15 presents. This is why a FIB operator sometimes produces eligible TEM samples and in other times he damages TEM samples unexpectedly with completely identical slicing conditions. So the trick 4 is that an excellent FIB application specialist should not just focus on FIB cutting parameters, but also need regard FIB beam's performance. When he finds obvious beam aberration through poor slicing quality, he need push service engineer to perform adequate FIB beam alignments.

IV. Conclusion

FIB/TEM sample preparation technique is a kind of profound skill for IC failure analysis. Since the high-end IC process' CD size reached down below 90nm, the FIB/TEM sample preparation has become more and more complicated. Generally FIB operators need care about some technic details to avoid TEM sample defects. In this article, the author introduces a couple of simple theories to explain how FIB beam interacts with sample and how TEM sample defects come out in some ways. In the meantime, a few tricks for FIB cross section cutting are presented for readers' reference. After all, understanding the failure mechanism of FIB/TEM sample preparation will be very helpful for FIB operators to take measures to keep TEM sample intact during FIB operations.

Acknowledgment

This paper was sponsored by Shanghai Sailing Program (17YF1426000). Thanks a lot to the nice people who helped behind.

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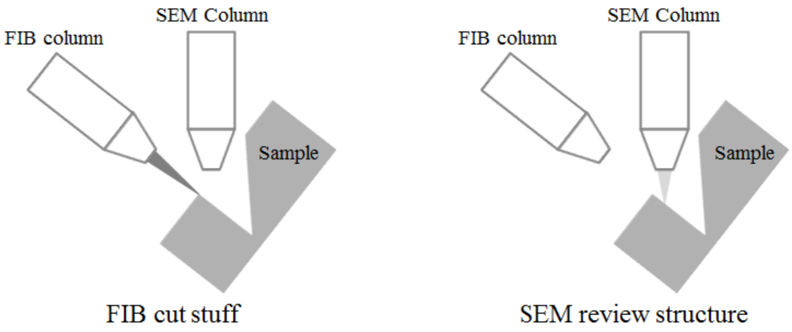

Fig. 1: Dual beam FIB tools' working mode for cross-section incising

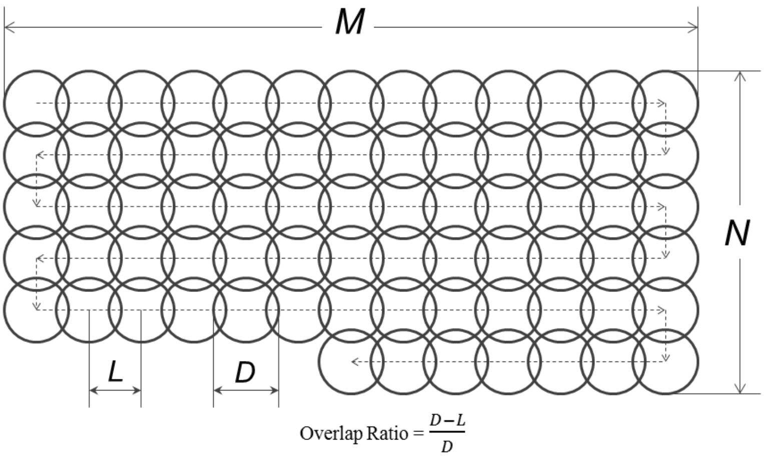

Fig. 2: FIB patterning incision working mode

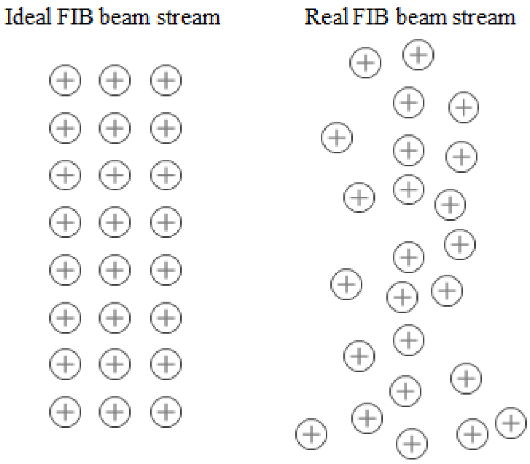

Fig. 3: FIB beam stream's Boersch Effect

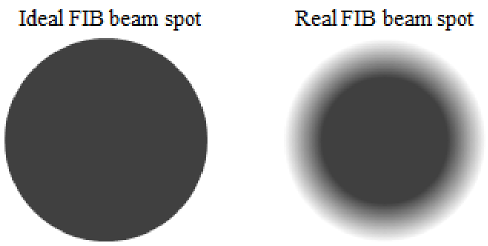

Fig. 4: FIB beam spot's simulation image in X & Y dimensions

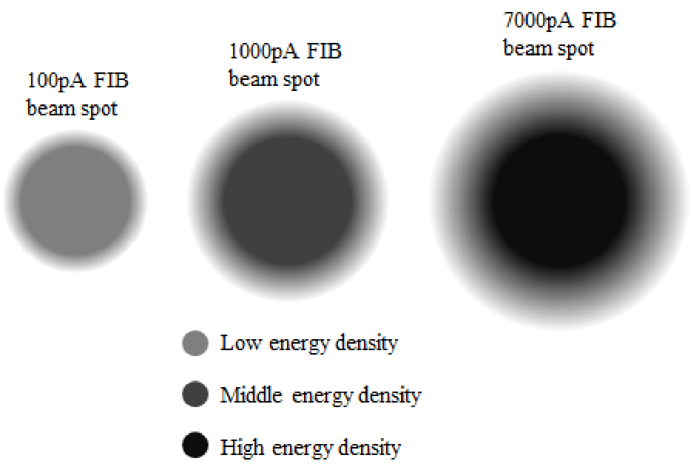

Fig. 5: FIB beam spots' energy density distribution

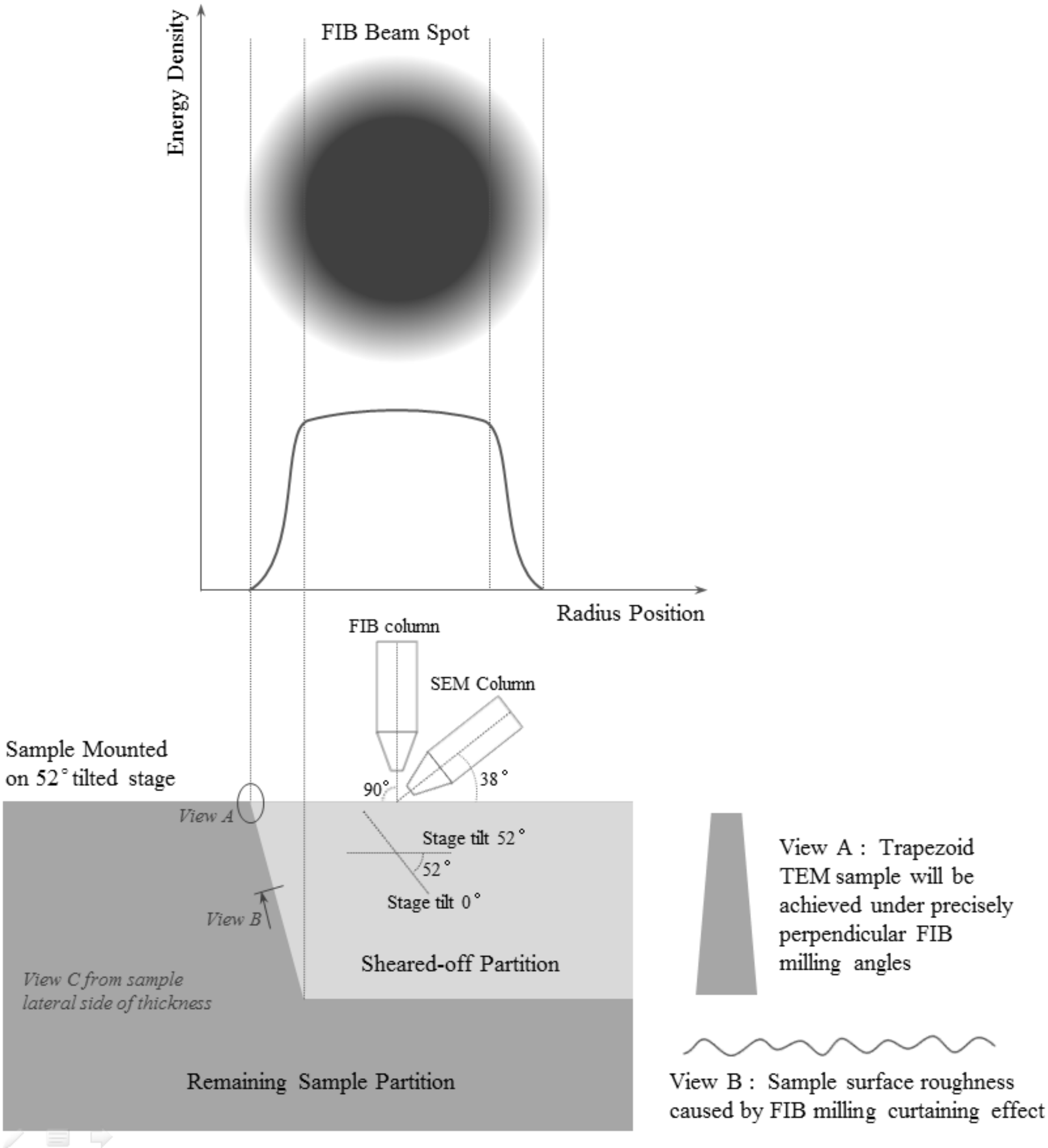

Fig. 6: FIB beam spots’ energy density distribution

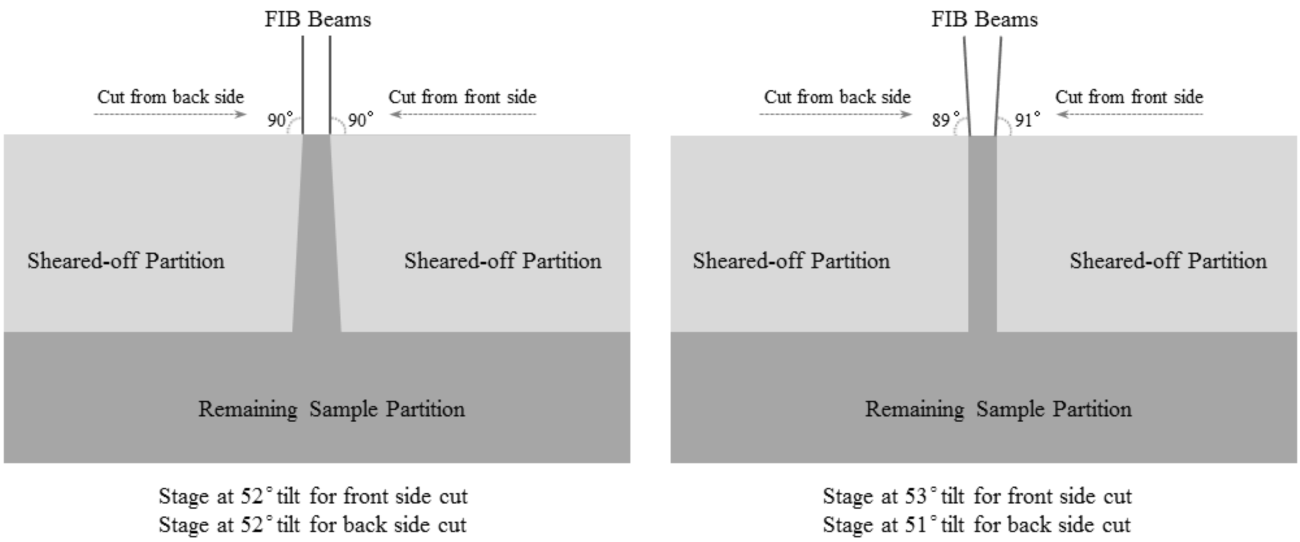

Fig. 7: Amended stage tilt angles for non-orthogonal FIB milling

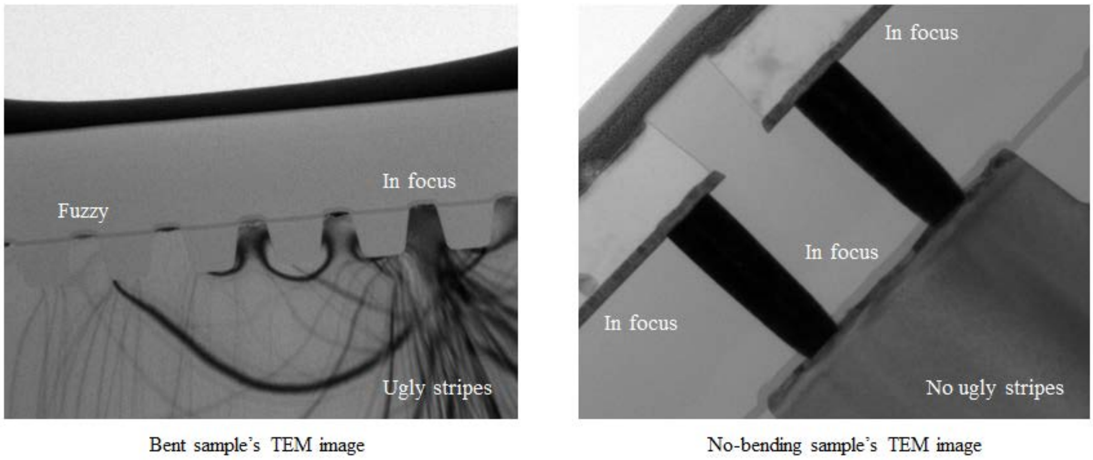

Fig. 8: Comparing bent sample and no-bending sample under TEM

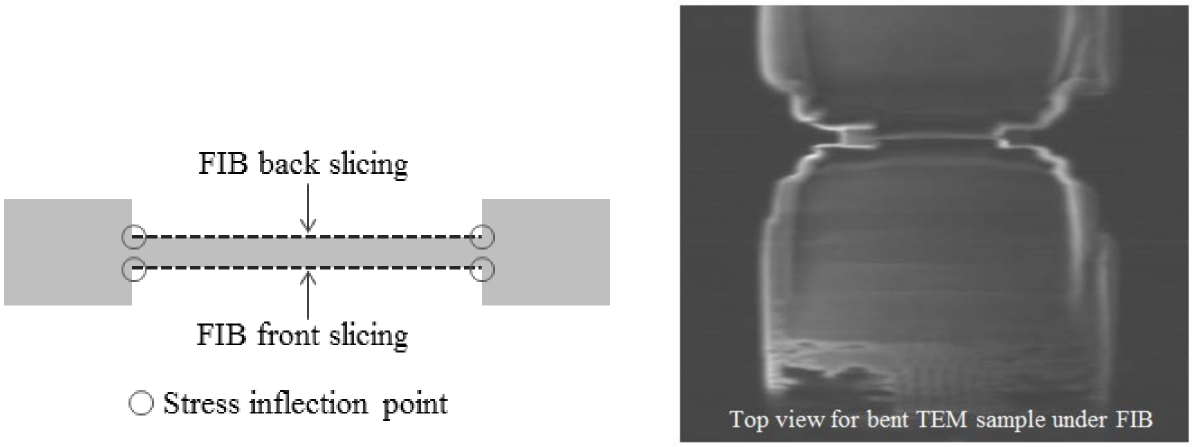

Fig. 9: Equal slicing width for front slicing and back slicing

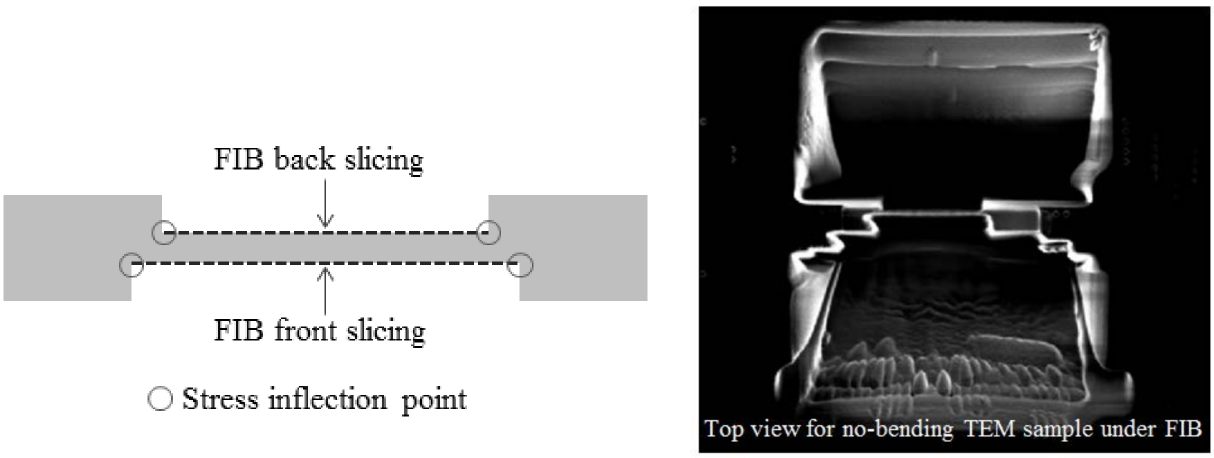

Fig. 10: Unequal slicing width for front slicing and back slicing

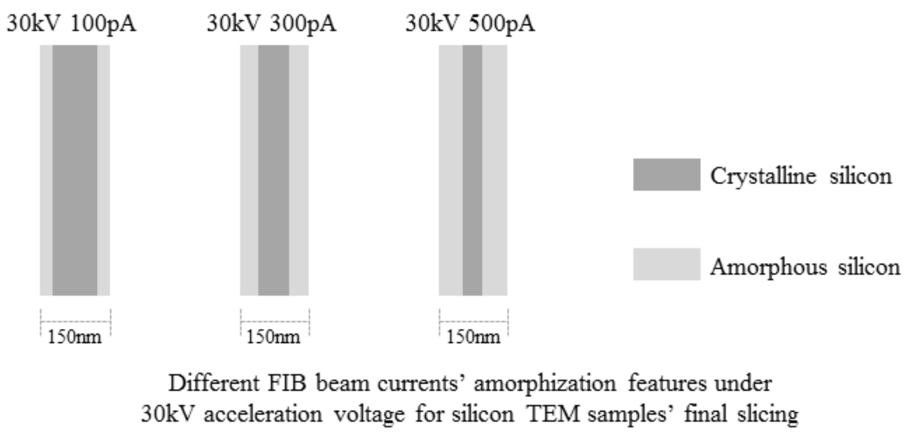

Fig. 11: TEM samples' amorphization effect under different FIB beam currents

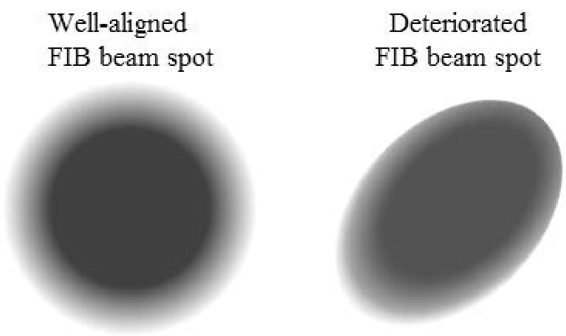

Fig. 12: Comparison of good FIB beam spot and bad FIB beam spot

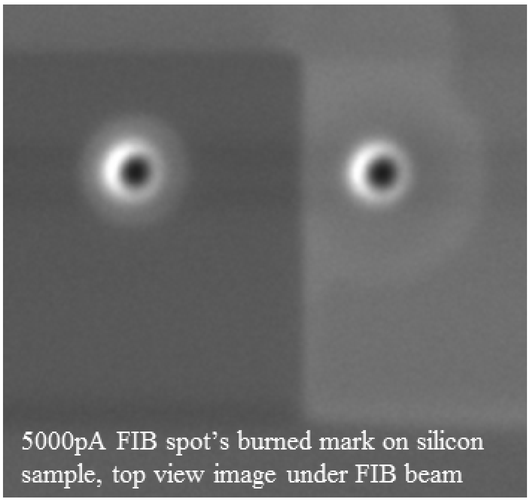

Fig. 13: Excellent burned marks by good FIB standing beam spots

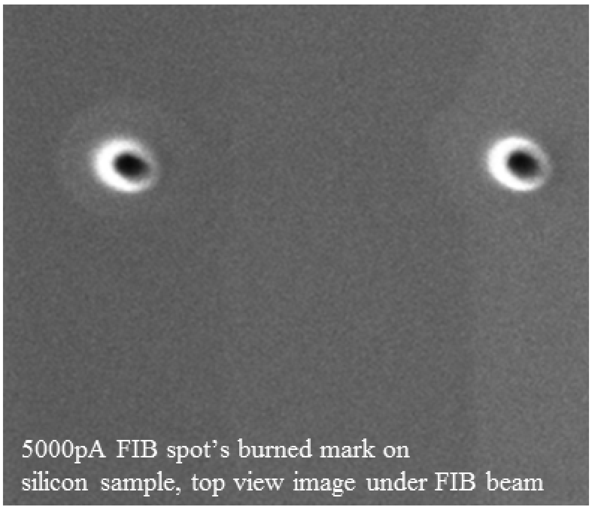

Fig. 14: Bad burned marks by aberrated FIB standing beam spots

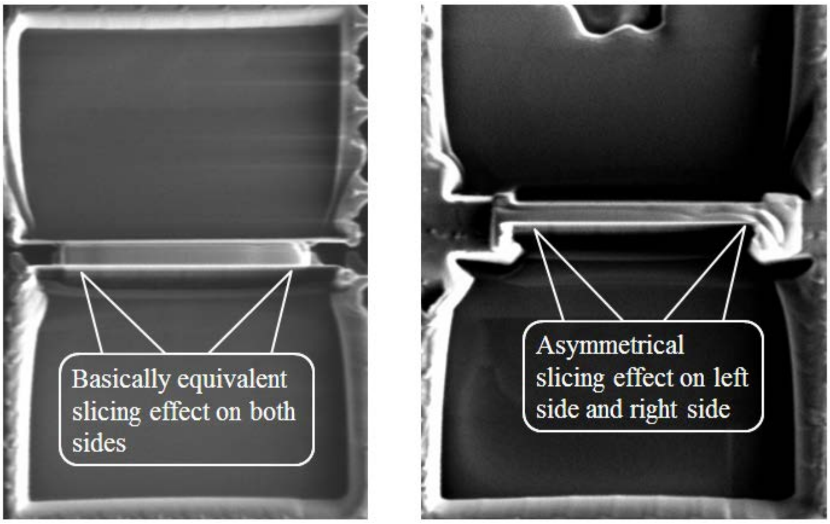

Fig. 15: Comparison of slicing effect by good FIB beam and aberrated FIB beam