Automating Reconstruction of Focused Ion Beam Current Density Distribution

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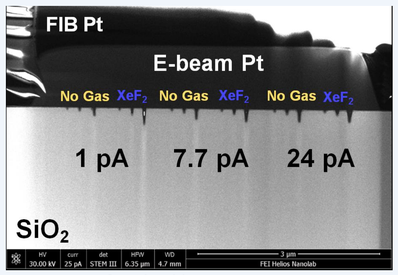
Introduction

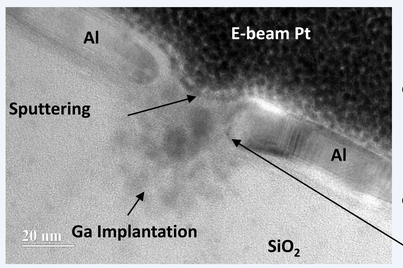
- Processing features with lateral dimensions comparable to diameter of Focused Ion Beam (FIB) on layers with thickness comparable to the depth of ion implantation demands understanding of FIB-to-material interaction within the area of ion beam impact. Developing such undestanding requires tools for estimating current density distribution within the area of single ion beam [1].
- FIB profile reconstruction methodology was recently developed[2], but relies on multiple HR-TEM micrographs and is difficult to implement with limited resources.
- We propose a simplified, simulation-based methodology for reconstructing the FIB profile from sputtering and implantation information available on cross-sectional TEM micrographs of the single beam width lines etched by FIB.
- The reconstructed beam profile was applied to analysis of a single line etching experiment to gain insight into details of gas-assisted etching and deposition[3] within the area of ion beam impact.

Single Beam-Width Etching Experiment

- Single beam-width lines were etched in polished fused silica substrate, coated by 24 nm of vacuum-evaporated Al, by 30 kV Helios 660 Ga^+ FIB. Beam currents of 1 pA, 7.7 pA, and 24 pA, dwell 25 nS, overlap -25%, and ion beam doses 0.2 nC/um^2, 0.6 nC/um^2, and 1.8 nC/um^2 were used to etch two groups of lines with each beam current: by physical sputtering and with XeF_2 gas-assisted etching precursor.
- TEM lamella was made after protecting area by E-beam Pt, followed by FIB Pt deposition.
- TEM images show two distinct regions of Ga implantation density.
- Ion recoil is evident from rounding inner edges of Al layer.



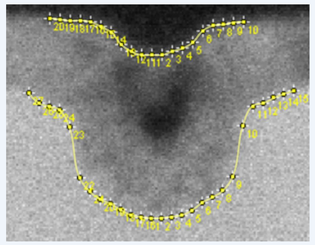
SEM of etched line cross-sections



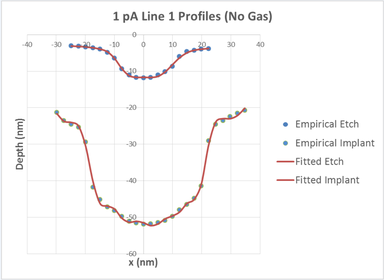
TEM micrograph of 1 pA, 0.2 nC/um^2 line

Manual Extraction of Etch and Implant Profiles

- Sputtering and implantation profiles were recorded in ImageJ from TEM micrographs.



Profile tracing in ImageJ

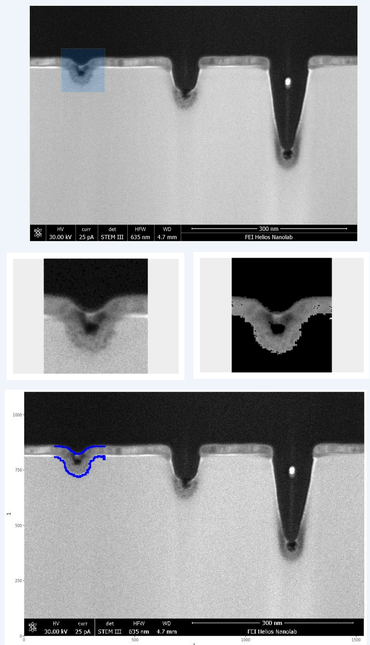


Gaussian fitted profiles

- Curve fitting in Origin and Matlab provided equations for profiles.

Automating Extraction of Etch and Implant Profiles

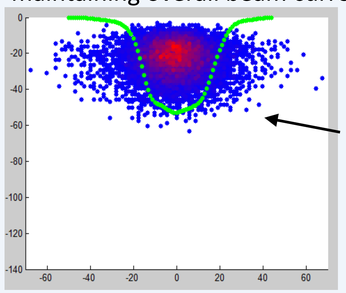
- Efficiency of extracting etching and implantation profiles could be greatly improved by implementing automated routines.
- Attempts of applying straightforward image processing techniques, such as thresholding (global and adaptive), sequential filtering, blurring, sharpening etc. did not provide satisfactory results.
- 2D spatial filtering and semi-automated interactive processing approach was developed and implemented with open source software: R[4], and related packages.
- At this moment algorithms follows the following steps:



- User select an area of interest
- The whole picture is divided to squares of a given size
- Mean (μ) and standard deviation (σ) of brightness of the squares in the top is calculated.
- Those squares with brightness within μ ± n*σ are made dark
- This is repeated for bottom part as well
- The remaining picture is used to find border lines
- Application in action can be found here https://cloud.ket-labs.com/shiny/FIB/

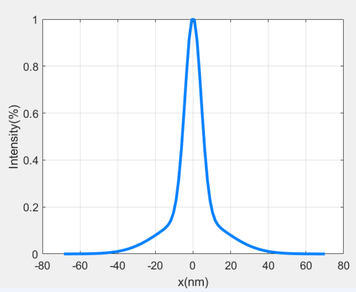
Applying Extracted Profiles to Reconstruction of Ion Beam Current Density Distribution

- Effective diameter of ion beam tails was assumed to be equivalent to largest width of ion beam damage visible on bright-field TEM images.
- Linear dependency of sputtered depth on ion dose was assumed for sputtering adjustment of ion trajectory launch point in TRIM.
- Bi-Gaussian beams were simulated with varied "Peak" and "Tails" parameters, while maintaining overall beam current value.

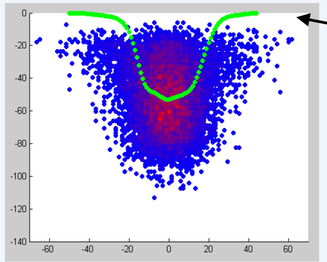


Simulated implantation of Ga into SiO2 is unsatisfactory match with experiment because of no correction for distribution of implantation along the depth of the single-line etching profile

Simulated Ga implantation in SiO_2 for 7.7 pA, 0.6 nC/um^2, no sputtering correction

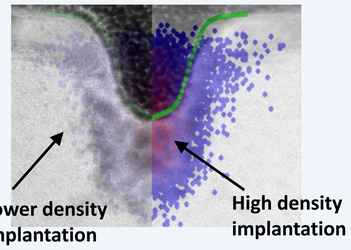


Example Bi-Gaussian beam profile



Automatically extracted etching profile could be used for correcting depth distribution of simulated Ga implantation

Sputtering-corrected Ga implantation in SiO_2 for 7.7 pA beam, 0.6 nC/um^2 dose



Overlay of adjusted for sputtering Ga implantation with TEM image

- Implantation with adjustment for sputtering can be iteratively simulated in SRIM, visualized in MATLAB, and compared with TEM of line profiles.
- Ion beam parameters resulting in simulated profiles with closest match to experiment were accepted as describing the primary ion beam.

Conclusions and Future Directions

- Developed 2D spatial filtering algorithm for detecting contrast variations on TEM and SEM micrographs and demonstrated capabilities superior to the basic thresholding.
- Demonstrated automated extraction of etching and implantation profiles from TEM micrographs of single-line etching by Ga^+ FIB into SiO_2 substrate.
- Deployed web-based application for detecting etching and implantation boundaries
- Exploring integration of spatial filtering and automated extraction of etching and implantation profiles with simulation-based methodology for reconstructing FIB current density profile from TEM micrographs of single-beam-width etching cross-sections.
- Planned work on automating comparison of simulated implantation with experimental implantation profile
- Reconstructing profiles of Xe^+ FIB with inherent low current density is of high interest.

Acknowledgements and References

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