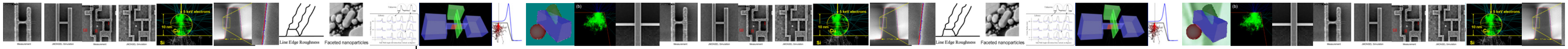


Modeling Scanning Electron Microscope Measurements with Charging

John S. Villarrubia

Semiconductor and Dimensional Metrology Division, Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD

ABSTRACT

TITLE:
Modeling Scanning Electron Microscope Measurements with Charging

BACKGROUND:
SEM (scanning electron microscope) measurements used by the semiconductor electronics industry for device characterization and process metrology (critical dimensions, defects,…) presently have poorly-understood errors arising from charging.

OBJECTIVE:
Include the physics of charging in the JMONSEL SEM simulator.

JMONSEL SIMULATOR DEVELOPMENT:
JMONSEL can now import tetrahedrally meshed samples, track trapped charges in the mesh, use finite element analysis (FEA) to compute the resulting fields, and account for the effect of fields on electrons.

APPLICATION TO CONTACT HOLE IMAGING:
The new capabilities have been used to simulate imaging of contact holes with 500 eV landing energy. The simulation shows that initial charge-up saturates quickly, producing a stable charge condition that is beneficial for seeing the bottom of the hole.

CONCLUSIONS:
JMONSEL now allows calculation of expected contrast for features on the hole bottom under varying measurement conditions. Pre-charging a large surface area increases the surface potential and improves signal from the bottom of the hole.

BACKGROUND

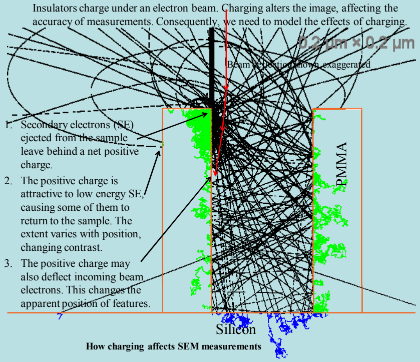
The Need:

The SEM (scanning electron microscope) is needed for high resolution metrology of integrated circuits, for example in critical dimension metrology or defect detection.

Insulating materials (e.g., resists, gate dielectrics, oxide spacers in interconnect layers, …) are important in integrated circuit manufacture.

The Problem:

Insulators charge under an electron beam. Charging alters the image, affecting the accuracy of measurements. Consequently, we need to model the effects of charging.



How charging affects SEM measurements

Existing capability:

We already have an SEM simulator: JMONSEL (Java MONte Carlo Simulator for Secondary ELectrons).

JMONSEL simulates electron transport, scattering, escape, and detection—but it did not include charging phenomena.

OBJECTIVE

Include the physics of charging in the JMONSEL SEM simulator.

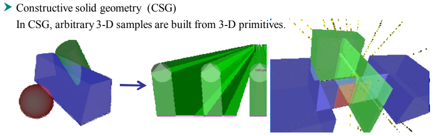
JMONSEL SIMULATOR DEVELOPMENT

OVERVIEW

- JMONSEL uses Monte Carlo simulation
- The beam can be raster-scanned (or any other desired scan pattern)
- At each beam landing position, and each electron, it models relevant scattering physics
- Emerging electrons may be filtered (e.g., for energy, angle, or position to simulate detector characteristics) and are used to construct an image.

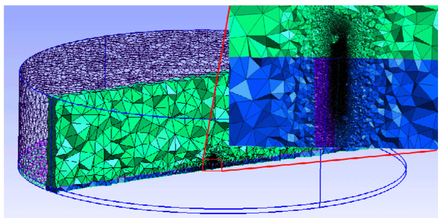
SAMPLE REPRESENTATIONS

- Constructive solid geometry (CSG)
  In CSG, arbitrary 3-D samples are built from 3-D primitives.



CSG shape primitives… …combine to describe more complicated samples.

- Alternatively, tetrahedral finite element mesh (new|this work)

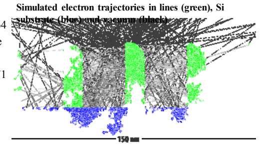


Tetrahedrally meshed Si SiO2 layer (blue) with vacuum (green) and contact hole (purple)

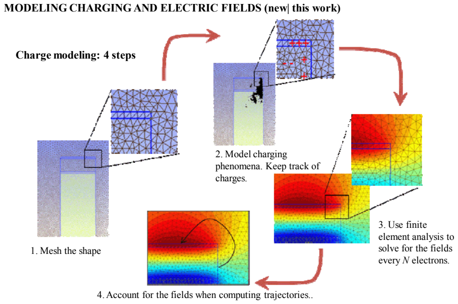
SCATTERING PHENOMENA INCLUDED IN THE MODEL

- Elastic scattering (electron/atomic nuclei)
  Uses NIST Standard Reference Database 64
- Secondary electron generation and cascade
  Dielectric function theory approach
  Uses NIST Standard Reference Database 71
- Phonon scattering
- Charge trapping
- Electron diffraction at material boundaries

Simulated electron trajectories in lines (green), Si substrate (blue) and vacuum (black)

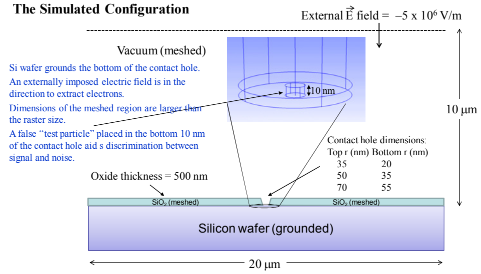


MODELING CHARGING AND ELECTRIC FIELDS (new| this work)



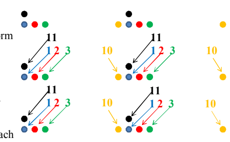
APPLICATION : CONTACT HOLE IMAGING

The Simulated Configuration



Simulated Measurement Procedure

- Beam landing energy is 500 eV.
- The beam is rastered 15 µm × 15 µm with 1 nm × 5 nm (x × y) pixels centered on the hole.
- During the charge-up phase, dosage is very uniform
  Dose is 1 electron per pixel.
  Only 1/1125 pixels is dosed on each pass.
  Skipped pixels are dosed on subsequent passes.
- FEA (finite element analysis) updates fields after each pass.
- A "frame" is complete after 1125 passes, when each pixel has received 1 electron.



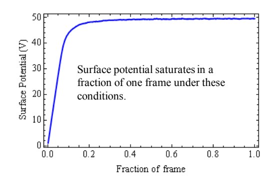
Raster order

- All electrons that exit into the upper hemisphere are assumed equally likely to be detected.

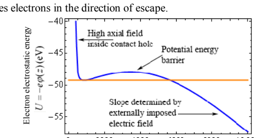
RESULTS

Results #1: The initial charge-up phase

- At this landing energy, average beam electron ejects more than 1 secondary electron (SE). Consequently, the SiO_2 upper surface potential becomes positive.
- The positive surface begins to recapture some low-energy SE. The yield decreases until it reaches 1, causing the charging to saturate. This happens very quickly:



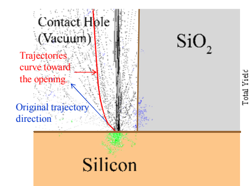
- At saturation, a potential energy barrier prevents all but the faster SE from escaping, and
- A very high axial field (~100 MV/m, 20× the externally imposed field) inside the contact hole accelerates electrons in the direction of escape.

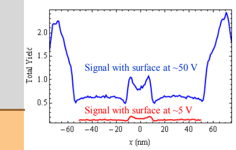


RESULTS (continued)

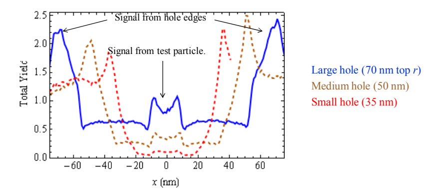
Results #2: The imaging phase

- With potentials stabilized we can simulate a line-scan across the center of the contact hole.
- **Dependence of signal on charged area:**
  The field inside the contact hole is beneficial. It helps extract secondary electrons.
  Larger charged area increases the surface potential and therefore this beneficial effect.





- **Dependence of signal on hole size:**
  The largest hole (70 nm radius at the top) exhibits good signal from the hole bottom, as judged by test particle (blue line).



Smaller holes (brown and red lines) exhibit reduced signal from the hole bottom. A factor of 2 reduced hole size causes a factor of 10 reduced signal. (Compare blue and red curves.)

CONCLUSIONS & FUTURE WORK

- Our JMONSEL SEM simulator has new capabilities:
  1. Accepts tetrahedrally meshed samples,
  2. Tracks trapped charges,
  3. Periodically computes fields by finite element analysis,
  4. Accounts for the effect of fields on electron trajectories.
- Application of the new capabilities to contact hole metrology provided insights:
  1. Under the conditions simulated, charging rapidly saturates with a positive surface potential.
  2. The charging is beneficial. It extracts signal electrons from the contact hole.
  3. The simulator can be used to determine signal vs. hole size.
- Future work / possible application areas:
  1. "What if" scenarios—limits of SEM, capabilities for 3D, FinFETs, defect inspection, etc.
  2. Best conditions for high aspect-ratio contact hole metrology.
  3. Critical dimension metrology of resist lines that accounts for edge shape.

For additional information please contact:

John Villarrubia
Semiconductor and Dimensional Metrology Division
Physical Measurements Laboratory
National Institute of Standards and Technology
John.Villarrubia@nist.gov