Surface redeposition and damage due to Focused Ion Beam milling

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Summary

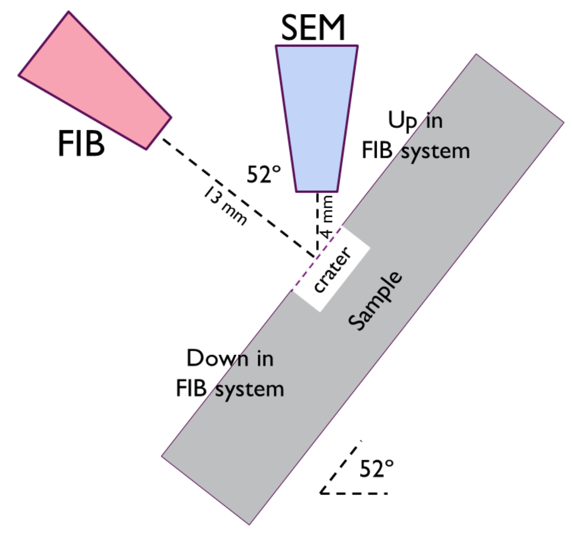
"Wafer return" is a possible work flow for microelectronics manufacturing allowing to continue wafer processing after analysis with FIB for local XSEM or extraction of lamellae for in-situ low-kV STEM or off-line TEM/STEM analysis.

Wafer return is only feasible if contamination on the wafer and cross-contamination to next processing tools remain below acceptable levels and device yield on the wafer is not affected. I.e. only the FIB'ed die should be lost by the FIBbing.

In this work we study the redeposition of milled material on the wafer surface and the electrical surface damage after milling conditions as typically used for TEM specimen preparation. The redeposition is characterized by TOF-SIMS analysis while the electrical surface damage is analyzed by micro four-point probe.

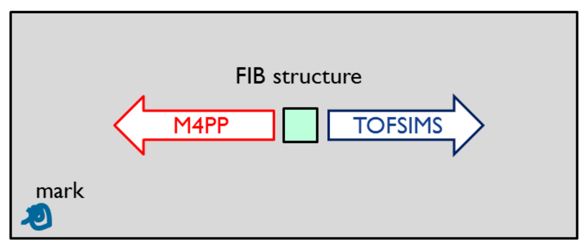
Experiments

FIB in Helios Nanolab 450HP
- Milling or deposition without grabbing images with the ion beam

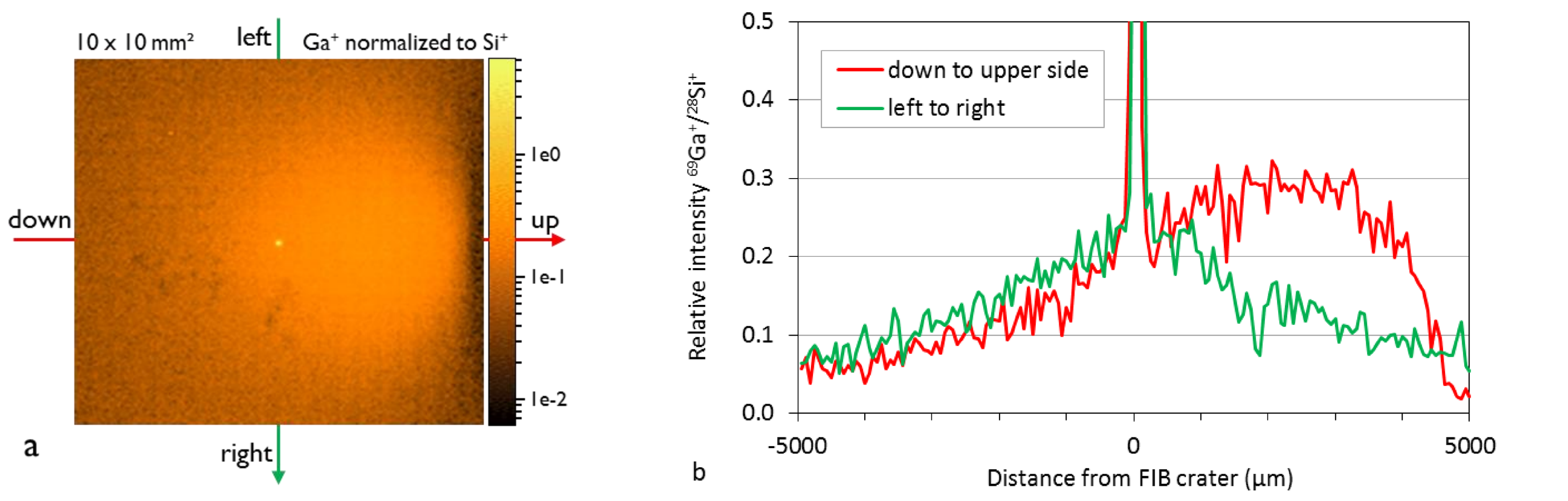


	FIB box or deposit	Ion beam conditions	Ga dose	
	µm³	kV, nA, s	nC	Ga ions
Si crater	10x10x1	30, 65, 12	780	$4.9\ 10^{12}$
Si crater	10x10x5	30, 65, 60	3900	$2.4\ 10^{13}$
Si crater	10x10x15	30, 65, 180	11700	$7.3\ 10^{13}$
Si crater	10x10x5	5, 13, 300	3900	$2.4\ 10^{13}$
Cu milling	10x10	30, 0.77, 150	116	$7.2\ 10^{11}$
Cu milling	50x50	30, 0.77, 3060	2356	$1.5\ 10^{13}$
Pt deposition	9x9.4x2	30, 0.4, 840	336	$2.1\ 10^{12}$
Pt deposition	8.7x8.7x2	5, 0.4, 840	336	$2.1\ 10^{12}$

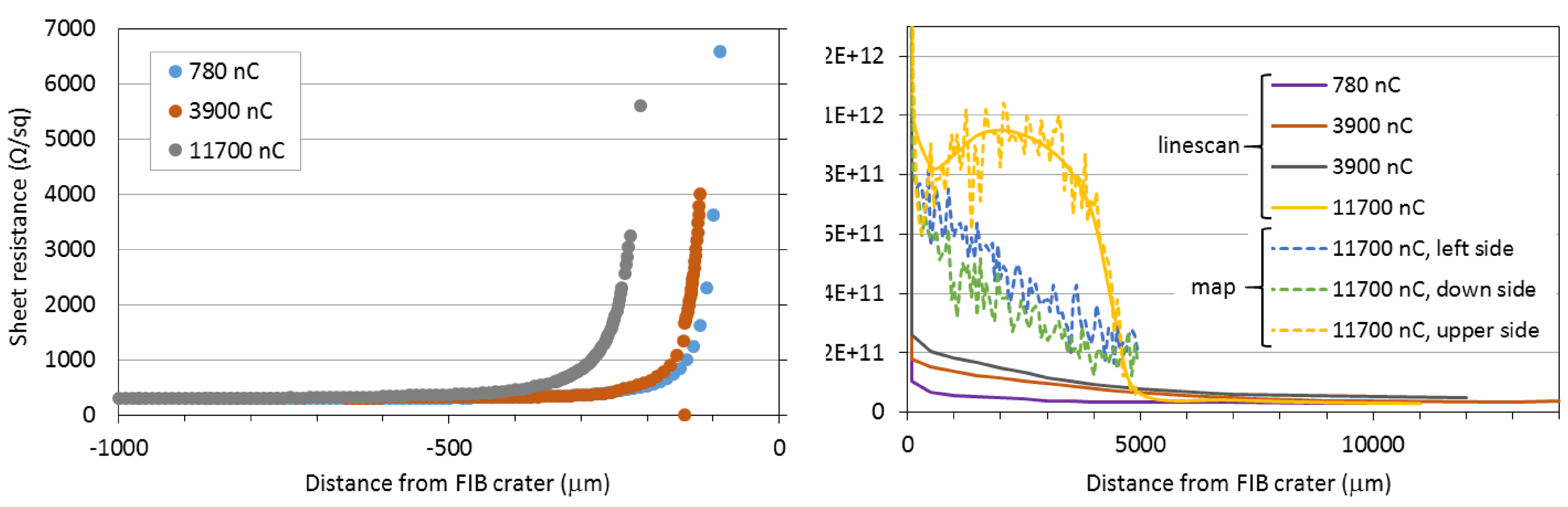
Analysis :
- M4PP : micro 4-point probe : electrical surface damage
- TOFSIMS : surface contamination



Ga milling in silicon

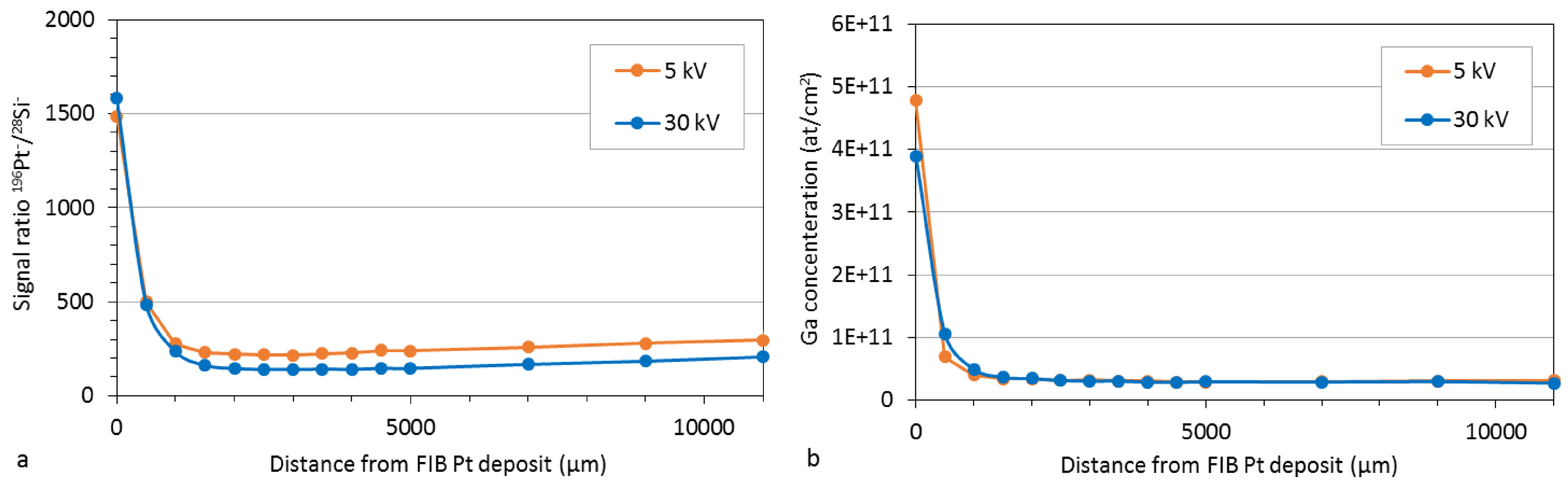


TOFSIMS mapping of the $^{69}Ga^+/^{28}Si^+$ intensity ratio over a 10x10 mm² area. The FIB crater in the center was milled with 11700nC dose. Line scans along the arrows on the map with the directions referring to the positions on the FIB stage. Redeposition is asymmetric around the crater.

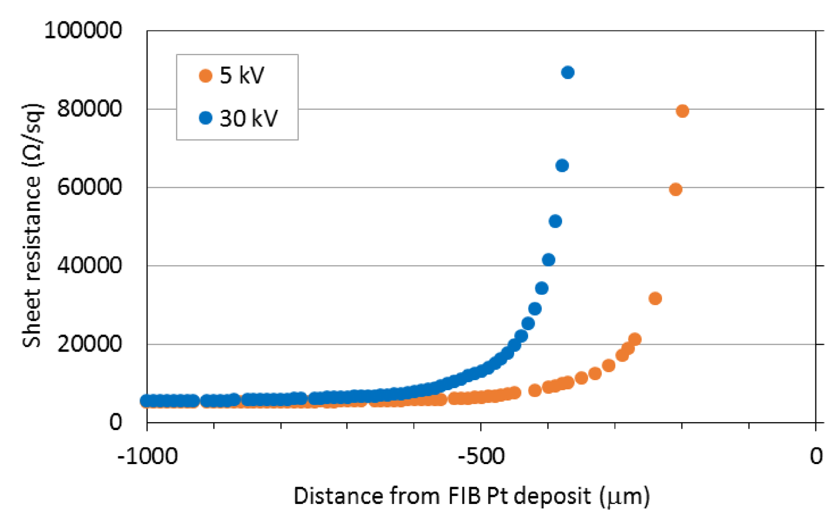


Dose dependence :
- Electrical damage range increases with dose and lasts till <0.5 mm from the crater. Electrical damage is symmetric around the crater (not shown).
- TOFSIMS Ga linescans along the downsides and from the map : redeposition drops to sensitivity level at 5 to 7 mm from the crater. Redeposition scales with dose.

Pt deposition on silicon

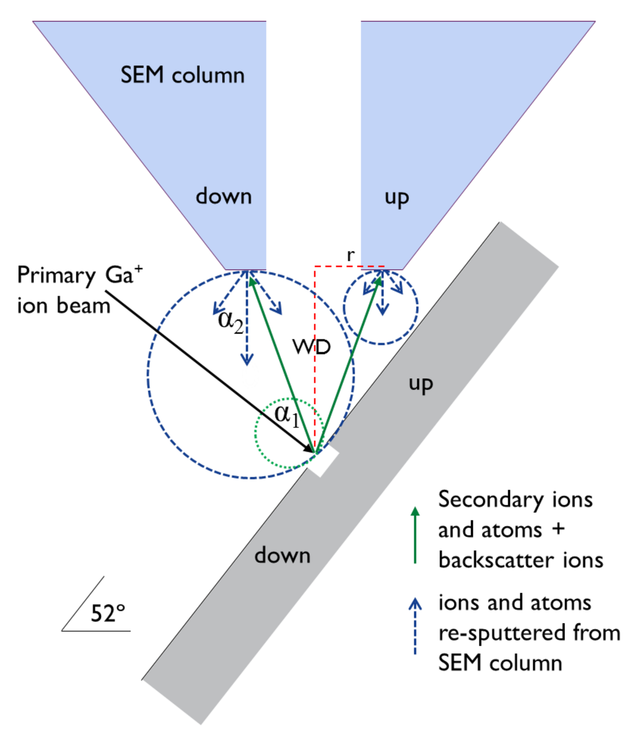


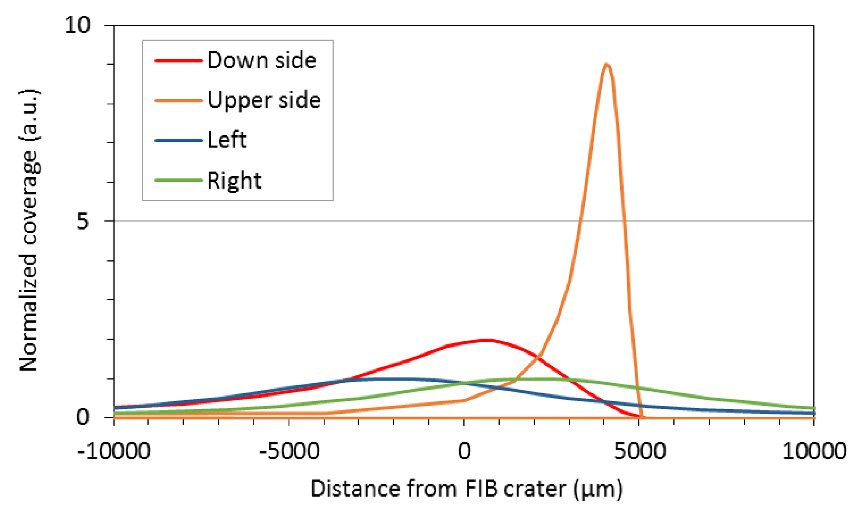
TOFSIMS $^{196}Pt^-$ signal relative to $^{28}Si^-$ and Ga atomic concentration next to FIB ion deposited Pt boxes. The $^{196}Pt^-$ signal is only above background for the first 3 points. As Ga dose is low compared to the crater milling also the Ga redeposition is low.



Sheet resistance line profile measurement away from the Pt deposits at 5 and 30 kV. Damage range is < 0.7 mm.

Mechanism of redeposition





Simulation of the contributions of redeposition through the bottom ring of the SEM column.
Shadowing by crater sidewall will lower the contribution from the upper side.

Schematic of the redeposition process during FIB milling on a tilted sample :
- Secondary ions and neutral atoms have cosine angular distribution : "no" direct redeposition on the surface expected.
- Ga has low ionization potential : large fraction are low energy secondary ions (<<100 eV) .
- Redeposition of the sputter Ga on the bottom of the SEM column : more redeposition on the "down" side.
- Increasing crater depth : redeposition on the "up" side of the column will be blocked by crater wall.
- Secondary ions have low sputter yield : e.g. 10^{-4} to 10^{-2} for 10 to 100 eV Ar, therefore more deposition than milling on the SEM column.
- Resputtering of the contamination layer follows again a cosine distribution which results in an asymmetric distribution on the tilted sample (red curve on the simulation).
- Redeposition range in the simulation is <5-7 mm as on the TOFSIMS map.

Conclusions

- Redeposition drops below TOFSIMS sensitivity (~5.10¹⁰/cm²) at <10 mm from the crater.
- Redeposition occurs through memory effect of the SEM column.
- Range of electrical surface damage is order or magnitude smaller (<1 mm). It is mainly due to beam tails.
- Redeposition will be less in single beam systems (larger distance to the FIB column)

Contamination and damage levels can be considered feasible for back-end of line processes with loss of only the analyzed die or potentially also its neighbor (ITRS spec 1.10¹²/cm²).
For front-end of line processes the acceptable contamination levels are more stringent and feasibility of wafer return will be more process specific (ITRS spec 1.10¹⁰/cm²).

Aspects as frontside/backside particle contamination, effects of thermal budget during further processing or additional cleaning steps to remove surface contaminants need to be taken into account as well to decide on feasibility of wafer return strategy.

Surface contamination and electrical damage by focused ion beam: conditions applicable to the extraction of TEM lamellae from nanoelectronic devices
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