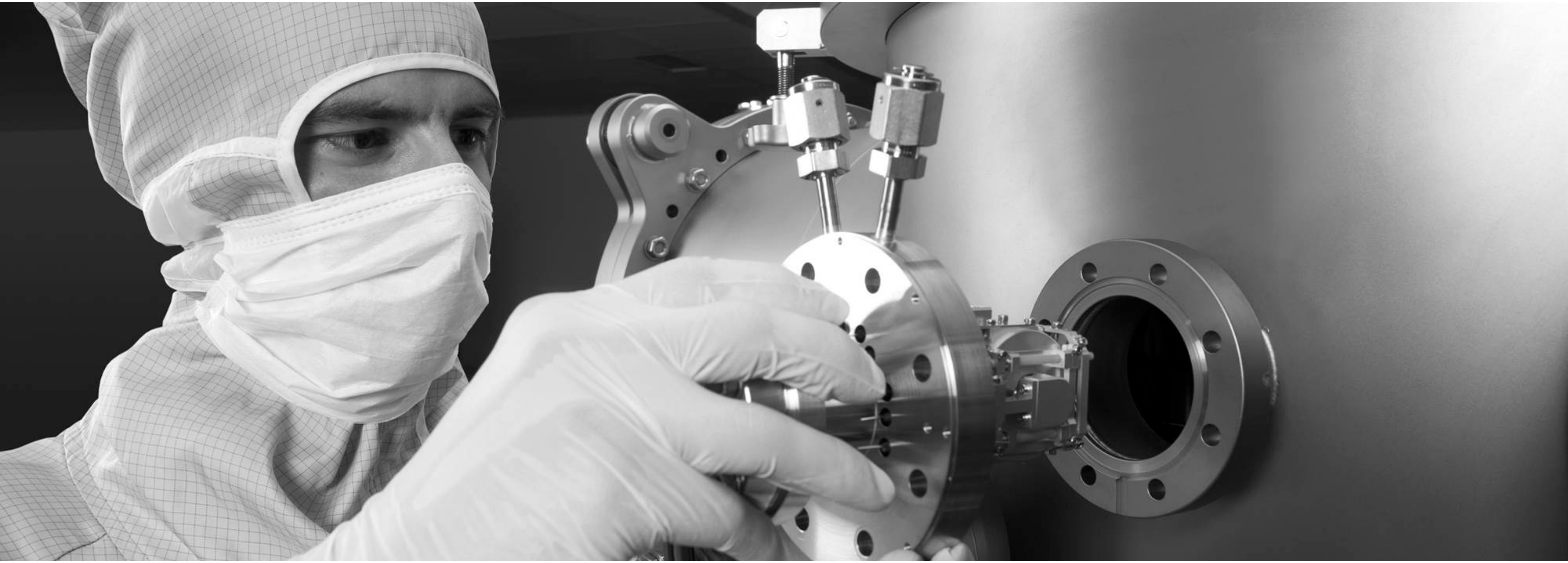
Development of a robust Fourier-Transform ion trap for semiconductor manufacturing



Valerie Derpmann

2018-10-18

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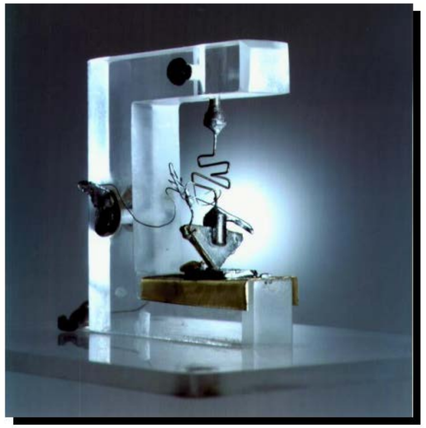
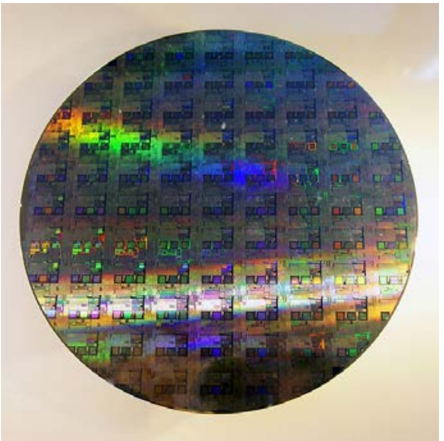
Introduction to semiconductor manufacturing processes

1947 The First Transistor from Bell Labs



- Reduction of structure sizes
- Reduction in prices
- Increase of reliability = less defects

300 mm processed Wafer



Million transistors on every die

General process categories
- Deposition (e.g. cvd)
- Removal (etch)
- Patterning (lithography)

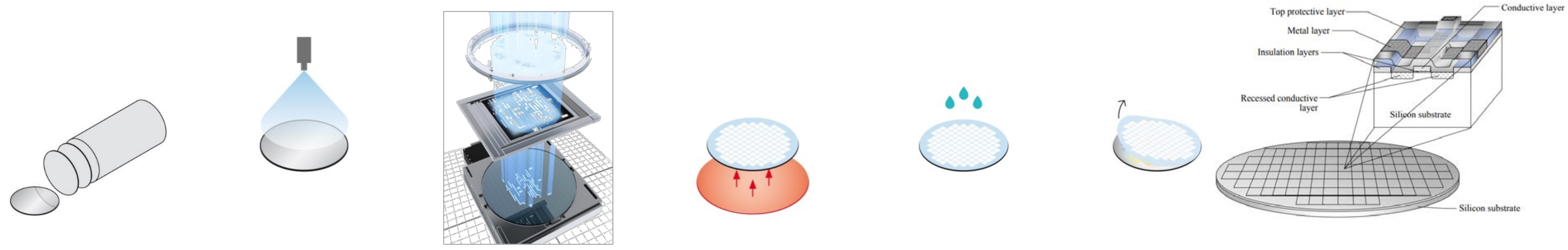
Process optimization:
- Time per process step
- More exact layer thicknesses and etching results
- Smaller lithography wavelength for smaller patterns

Photo courtesy of Lucent Technologies Bell Labs Innovations

https://commons.wikimedia.org/wiki/File:12-inch_silicon_wafer.jpg

Wafer processing

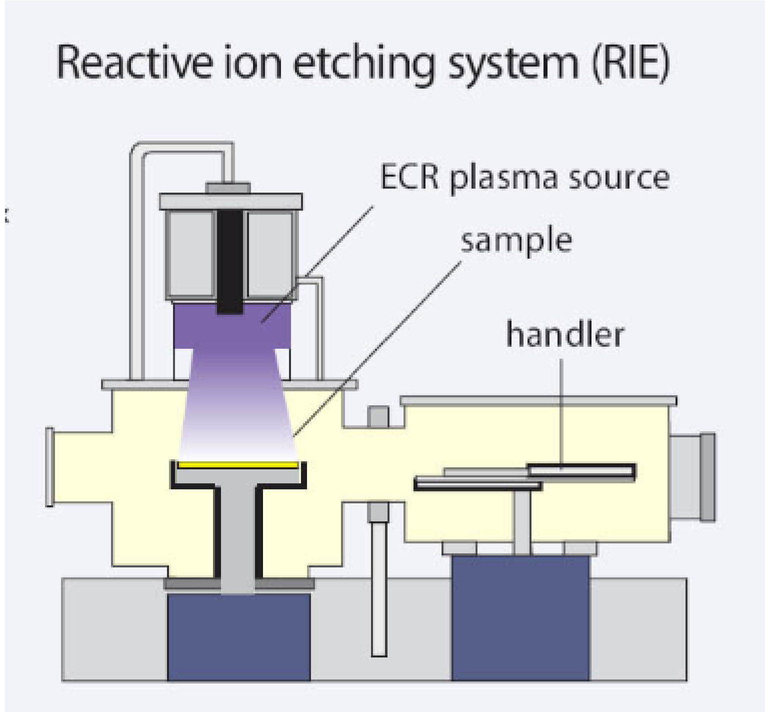
Wafer cutting and polishing → Resist coating → **Imaging** → Development & post exposure bake → Structural processing → Resist removal → Finished wafer



ZEISS ASML

40-60x

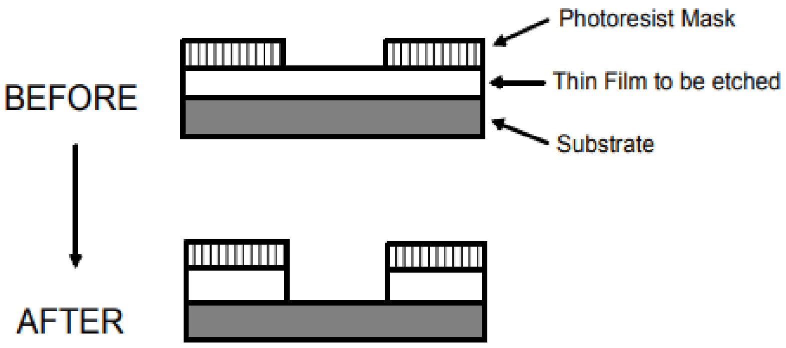
Semiconductor processes: Dry Etch



http://www.emrl.de/r_m_6.html

Pressure inside the etch chamber:
0.1-100 Pa

Etching result:



Endpoint detection necessary, to prevent over-etching and reduce process time

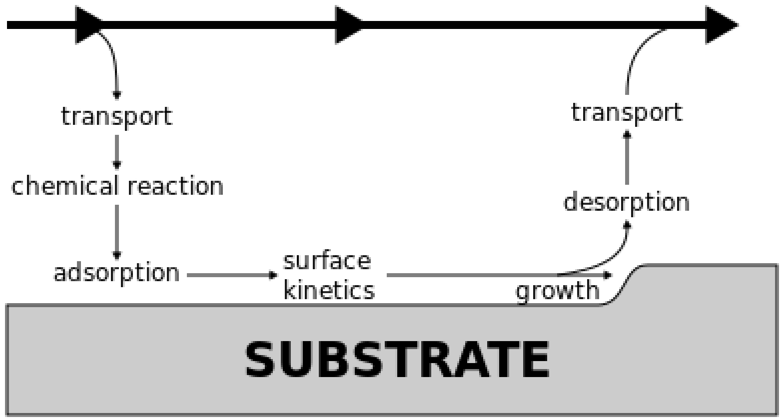
For Example:
$4F + SiO_2 \rightarrow SiF_4 + O_2$

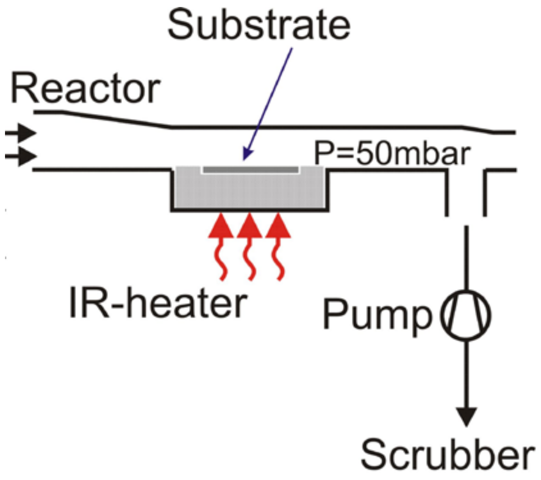
Film	Process gasses	Annotation
SiO_2, Si_3N_4	CF_4, O_2	F etches Si, O_2 removes carbon
	CHF_3, O_2	CHF_3 acts as a polymere, increases selectivity agains Si
	CH_3F	enhanced selectivity of Si_3N_4 against SiO_2
	C_3F_8	increased etch rate compared to CF_4
Poly-Si	BCl_3, Cl_2	no contamination by carbon
	$SiCl_4$, Cl_2 / HCl, O_2 / $SiCl_4$, HCl	
	HBr / Cl_2 / O_2	enhanced selectivity against resist and SiO_2
	SF_6	high etch rate, fair selectivity against SiO_2
	NF_3	high etch rate, isotropic
mono crystalline Si	HBr, NF_3, O_2 / CF_3Br	higher selectivity against SiO_2
	BCl_3, Cl_2 / HBr, NF_3	

https://www.halbleiter.org/en/dryetching/etchprocesses/

Semiconductor processes: MOVPE

- Metal organic vapor phase epitaxy
- Growth of crystalline layers of III/V-semiconductors, e.g. GaAs
- Organometallic precursors, like trimethyl gallium, tertiarbutyl arsine
- Temperature inside the reactor is up to 1000°C
- Pressure approx. 50 mbar





https://de.wikipedia.org/wiki/Datei:MOVPE_surface_processes.svg
https://www.rit.edu/kgcoe/microsystems/highlight/movpe-equipment-changes-everything-semiconductor-processing

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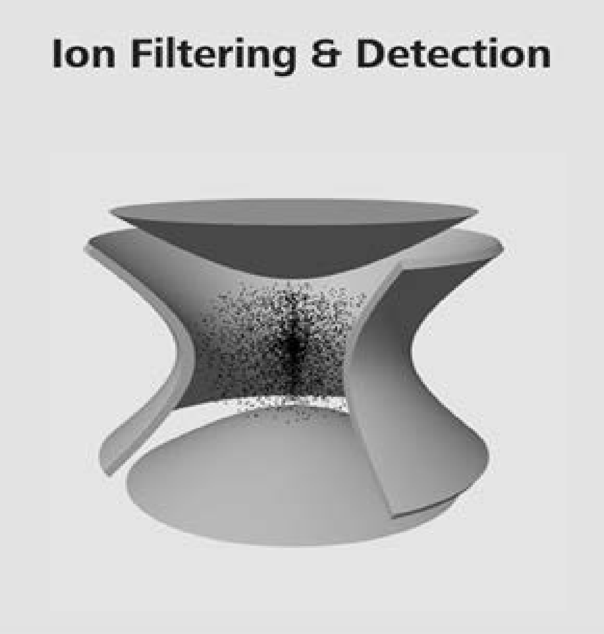
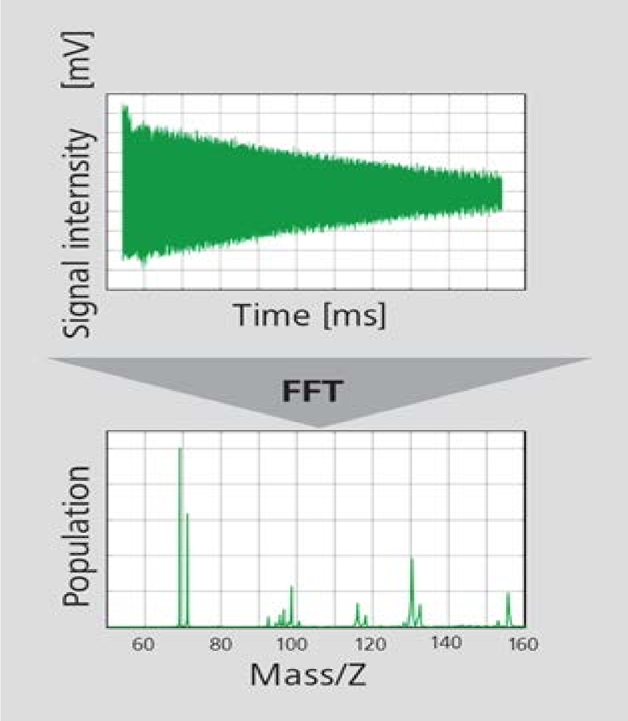
iTrap Working Principle

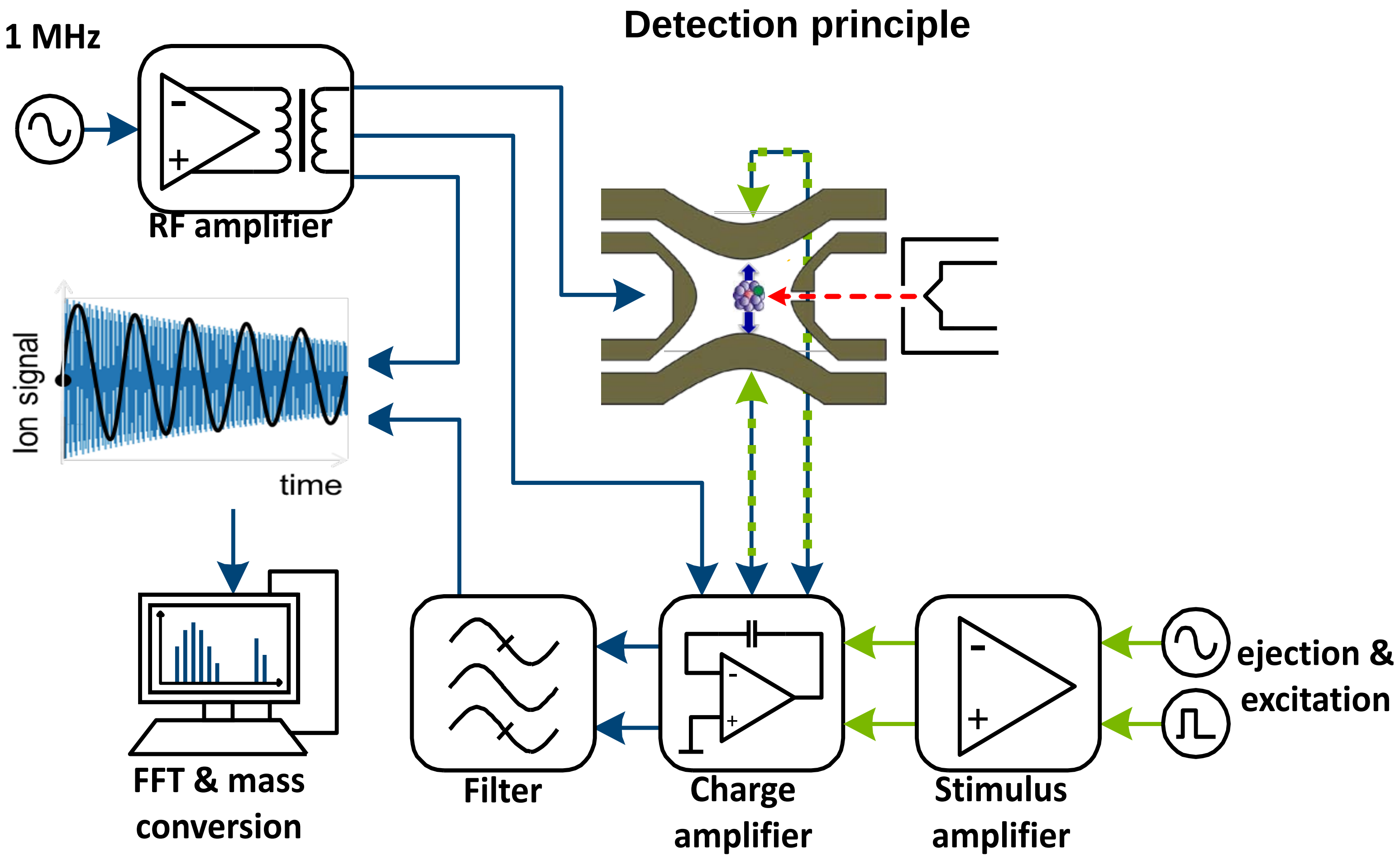


- EI (70 eV) is used to generate ions
- Ions are trapped in 3D quadrupole by HF electric field
- Ion oscillation frequency directly relates to m/z ratio
- Metal electrodes detect superposition of electrical signals of all ions
- FFT of electrical signal yields full mass spectrum in a single shot



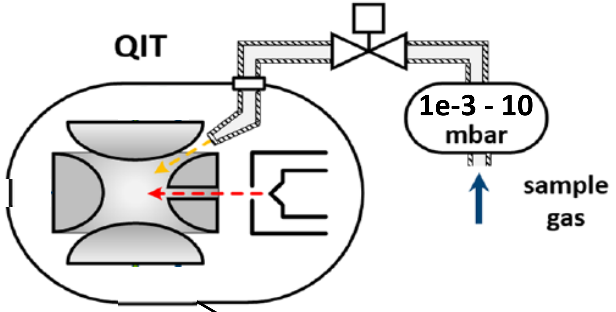
- All ion species in a spectrum can be **measured simultaneously without scanning**
- Ion species can be selectively accumulated and measured
- The same ion population can be repeatedly measured time after time to **improve S/N ratio**
- Measurement speed up to **2 Hz**

Experimental Setup and detection principle

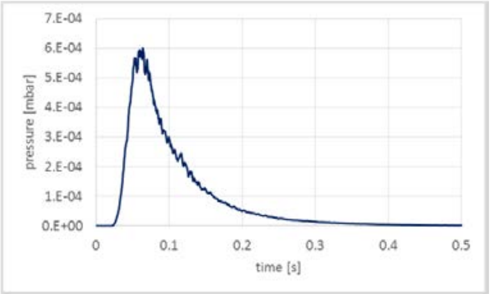


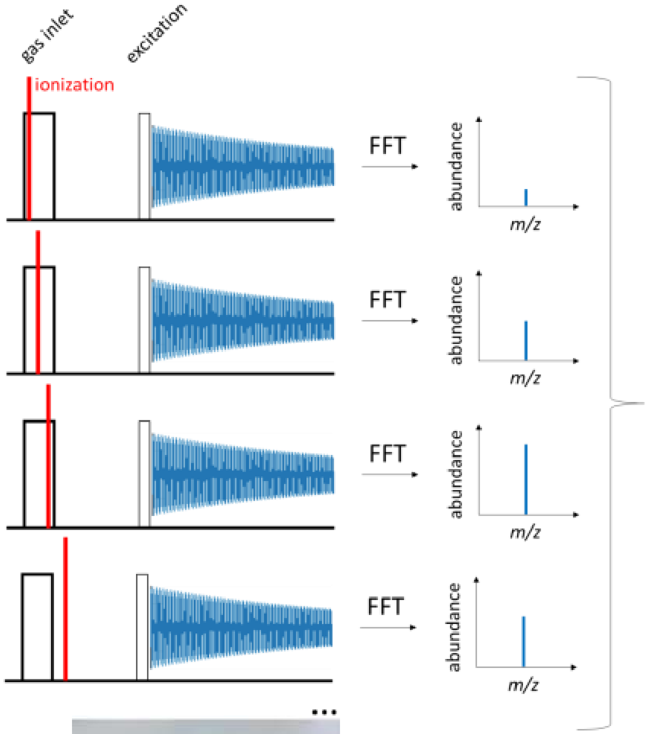
Robustness ensured by a reduced gas load and inert surfaces

- Pulsed gas inlet helps to reduce the gas load inside the trap

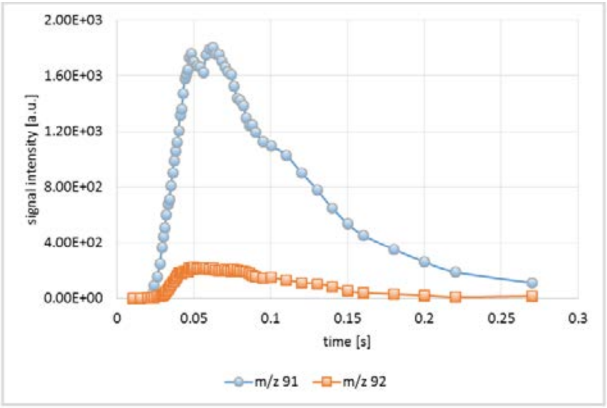


Pressure inside vacuum chamber



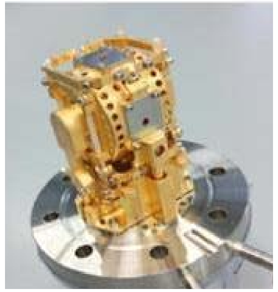


Time resolved measurement analyte response



Low gas load, but high pressure during ionization

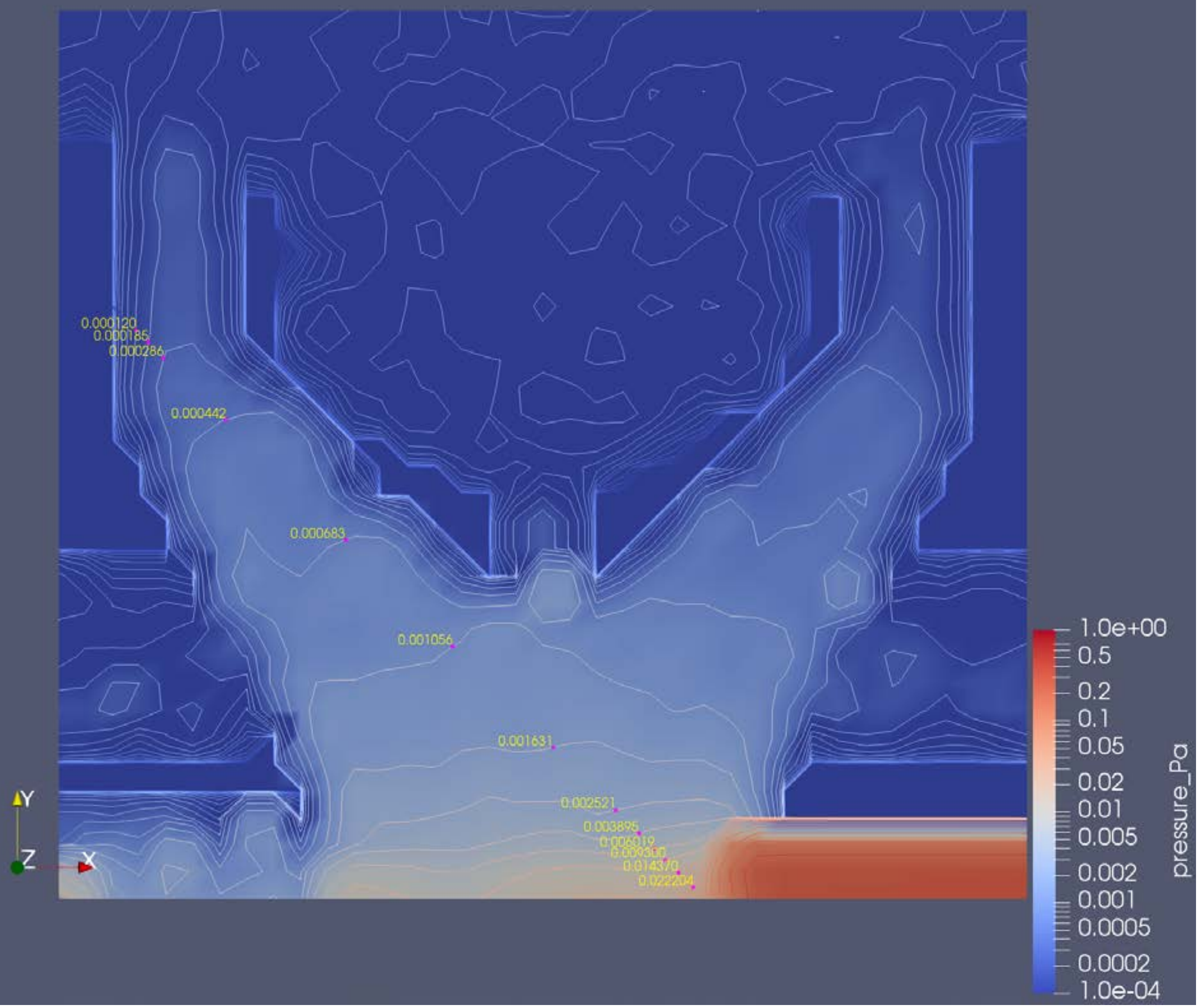
- All surfaces gold coated or made from Al2O3 ceramics
  → Corrosion is minizmized



- FFT instrument → No detector

Pressure inside the iTrap: DMSC Simulation

For 1 Pa inlet pressure

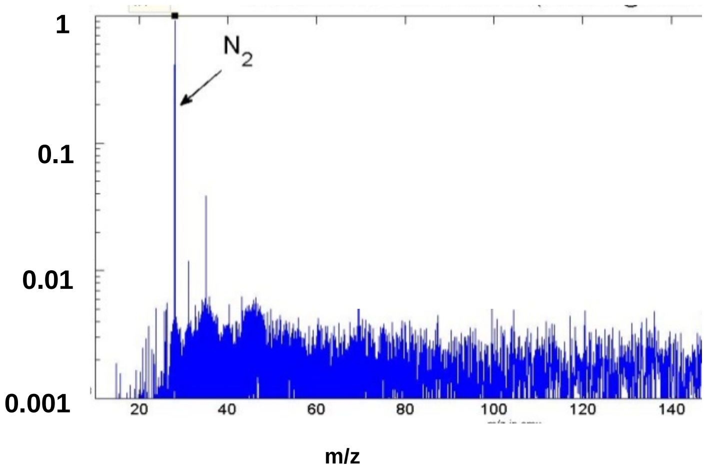


Selective ion trapping is used to increase dynamic range

Exemplary Use Case

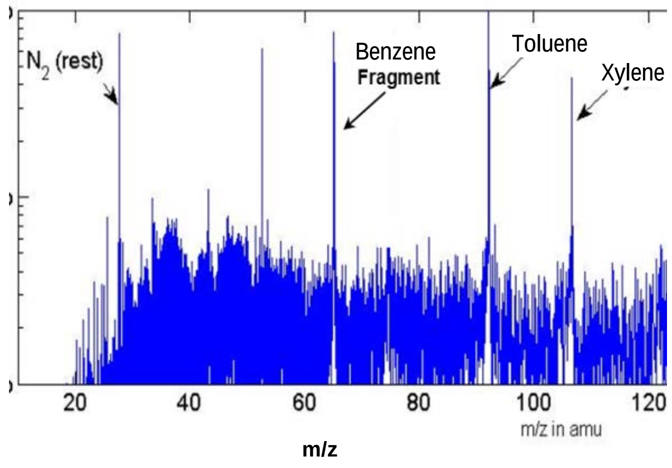
- Detection of BTX spectrum in N_2 carrier matrix (N_2 with 50 ppb Benzene/Toluene/Xylene)

Step 1: Measure



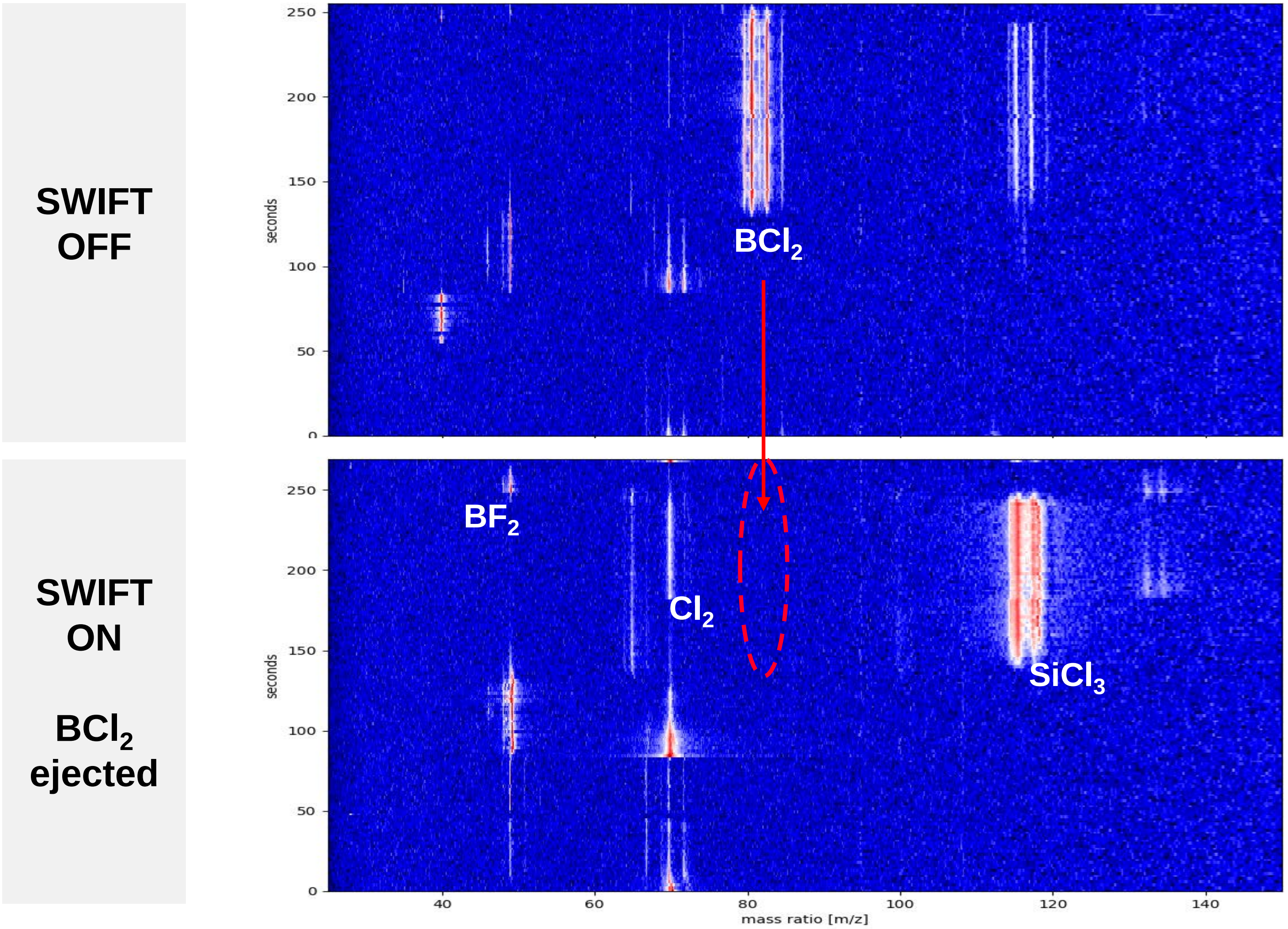
Spectrum is dominated by peak of N_2 carrier gas

Step 2: re-measure w/o matrix



- N_2 is removed
- Spectrum is re-measured
- BTX peaks become clearly visible

SWIFT* at work: Lower detection limit can be significantly enhanced



Overview of full mass range at almost real time.

Etch precursor BCl_2 dominates the spectrum and eats up dynamic range of the analyzer

SWIFT removes dominant species from the trap.

Species not visible before like BF_2, Cl_2, $SiCl_3$ are observed.

*Stored Waveform Inverse Fourier Transform

Agenda

iTrap Applications

Process Chamber
Epi, CVD, Etch

In-/Outgoing Wafer

Chamber Health

- Evaluate **effectiveness of pre/post cleans** in eliminating contaminant species e.g. metal halides
- Detect **Wafer to wafer** variation and within lot variation
- Identify **mismatched chambers** and do root cause analysis faster
- Monitor byproducts to **predict chamber lifetime** ahead of inline signals
- Proactively guard against **atmospheric leaks**/changes in **incoming gas purity** and composition

Process Control

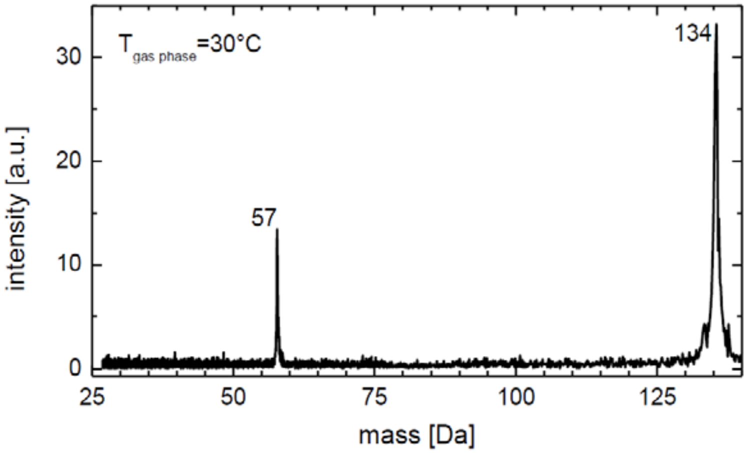
- **End Point** Critical Etch Processes based on mass spectra changes
- Evaluate **etch byproducts** to optimize chemistry selection e.g. fluorocarbon gas selection during oxide etch, such as C4F8 vs C4F6
- Watch real time **evolution of etched species** during testing to targeting critical threshold parameters e.g. temperature, RF Power
- Assess size of **process window** by response of mass spectra to parameter variation

Wafer Health

- Measure post process **outgassing** to target cleans/minimize queue time vulnerabilities
- Track long term changes in etch byproducts to monitor incoming material composition / depth uniformity

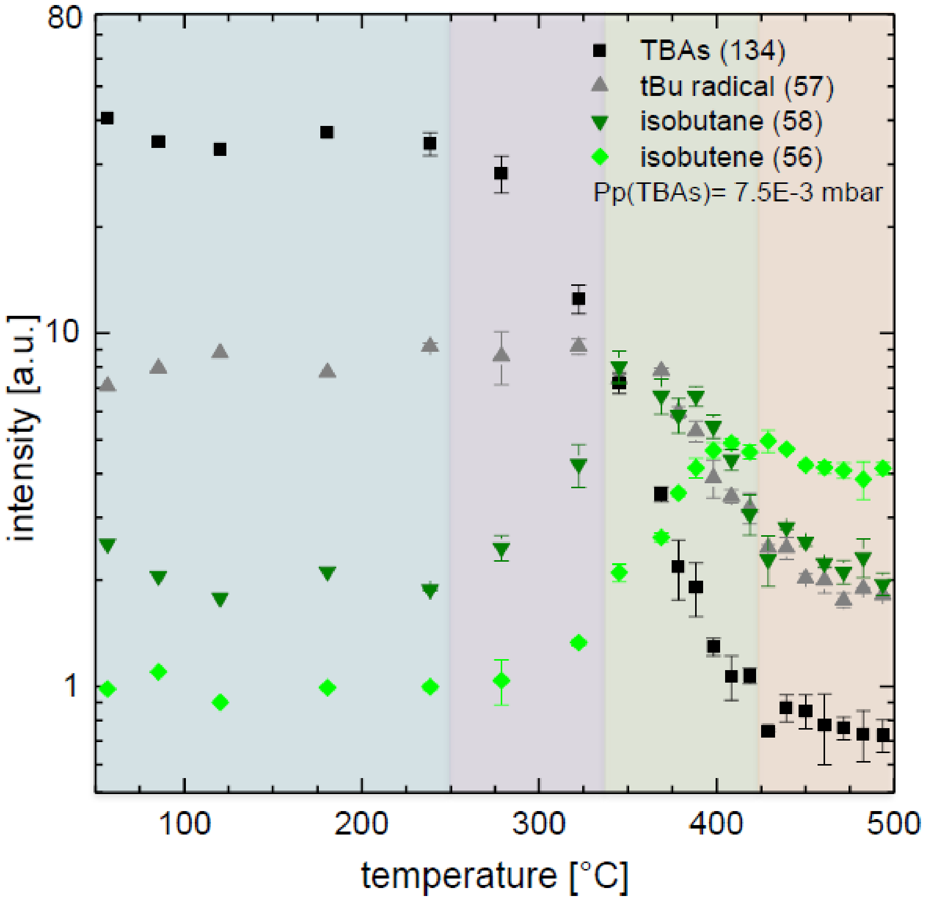
Process Yield / Uptime / Tool Matching

Investigation of TBAs decomposition in MOVPE reactor system



Mass spectrum of TBAs at 30 °C with a TBAs partial pressure of 7.5E-3 mbar

m/z 134 = TBAs
m/z 57 = tBu group



Reactor pressure: 50 mbar
Partial pressure TBAs: 1E-2 mbar

- no thermal decomposition
- just TBAs and tBu radicals due to EI cracking
- Isobutene/isobutane are at noise level

- thermal decomposition of TBAs initiated
- radical decomposition mechanism (increasing tBu radical signal)

- at T_{gas} > 330°C decomposition due to β–h-elimination becomes the important process
- tBu signal decreases due to increasing β–h-elimination and decreasing TBAs level

- saturation at T_{gas} > 450°C
- no TBAs signal
- tBu signal tracked by isobutane

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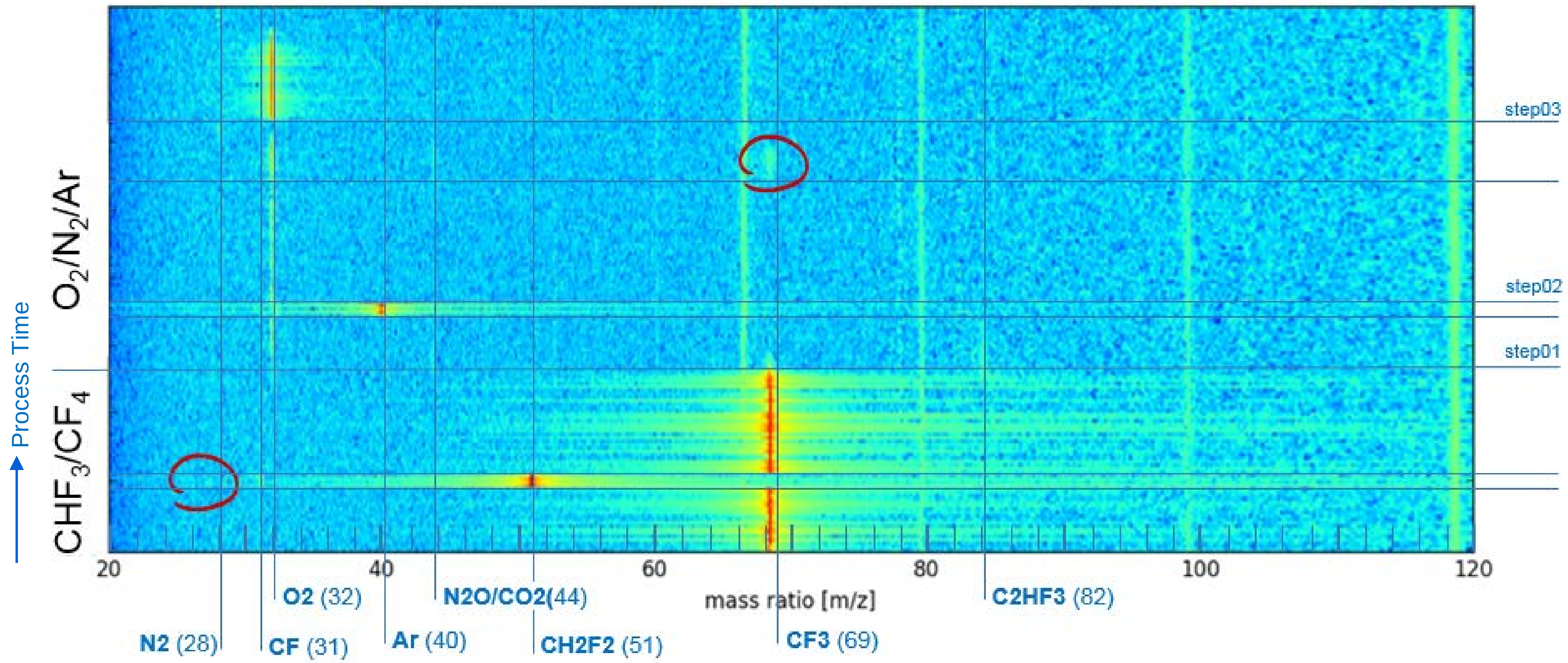
Process monitoring

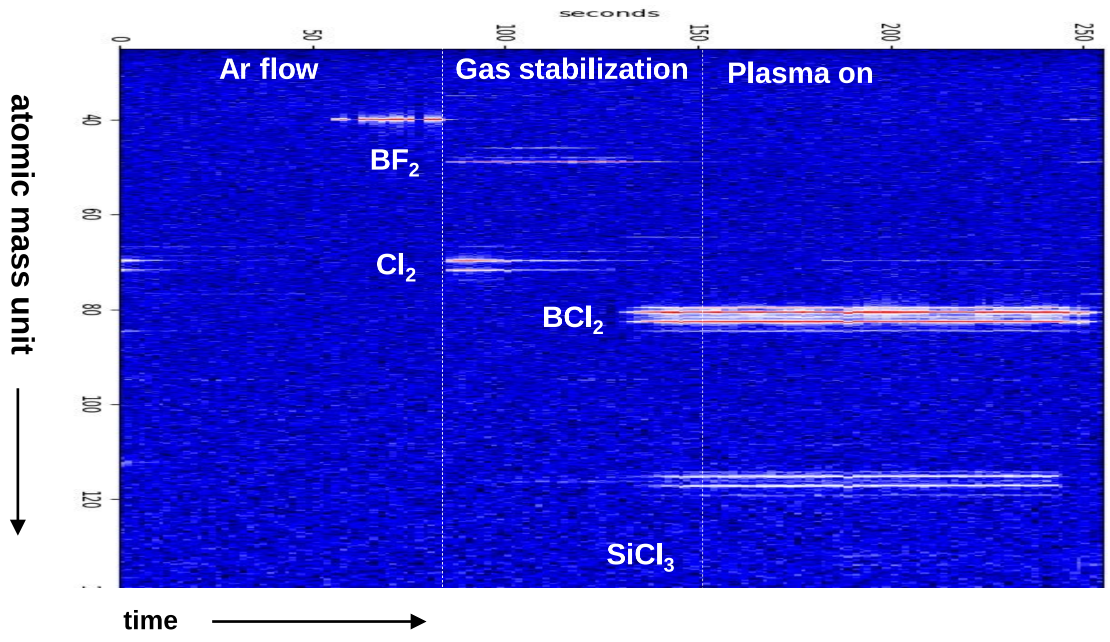
iTrap visualizes precursors, reaction products and contamination in your etch chamber

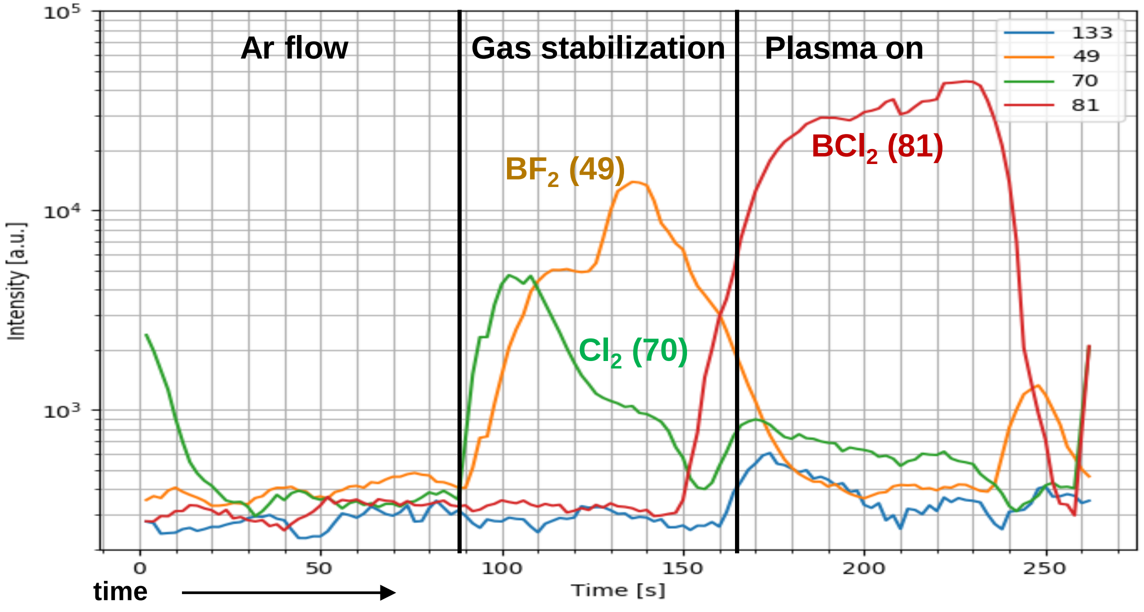


Process Failure?	**Run-to-run variations?**	**Process Drift?**	**Memory effects?**	**Conta-mination?**	**Correlation with other metrology (e.g. optical)**

Real time etch process optimization

TCP/ICP etch chamber /low pressure regime (2-10 mT), BCl_3 etch, SiO_2 wafer

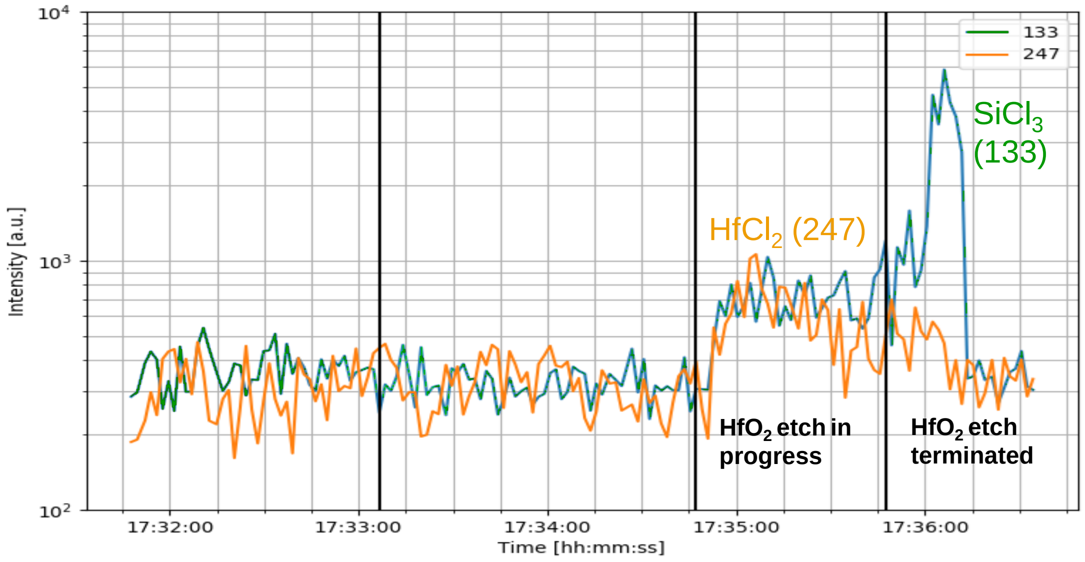




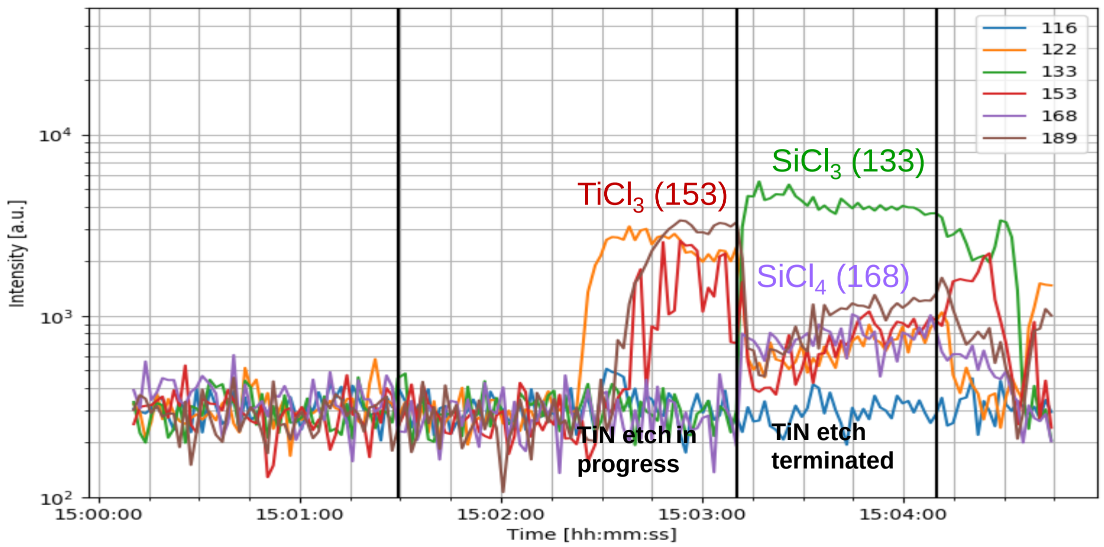
- iTrap allows study of etch reaction products as a function of pressure, concentration and previous cleaning steps
- Monitoring of chamber chemistry also **during plasma off**
- Correlation with etch rates enables ultrafast process optimization on the basis of real time iTrap data

End point detection

HfO_2 Etch process



TiN Etch process



Heavy species like $SiCl_3$, $TiCl_3$, $SiCl_4$, $HfCl_2$ can be monitored, also in non-plasma conditions.

Conclusions

- We developed an ion trap for semiconductor process control

- Fast processes can be easily examined in real time

- Robustness of the instrument is realized by:
  - Reducing the gas load inside the instrument, while ensuring a high pressure during ionization
  - selecting inert materials
  - No detector

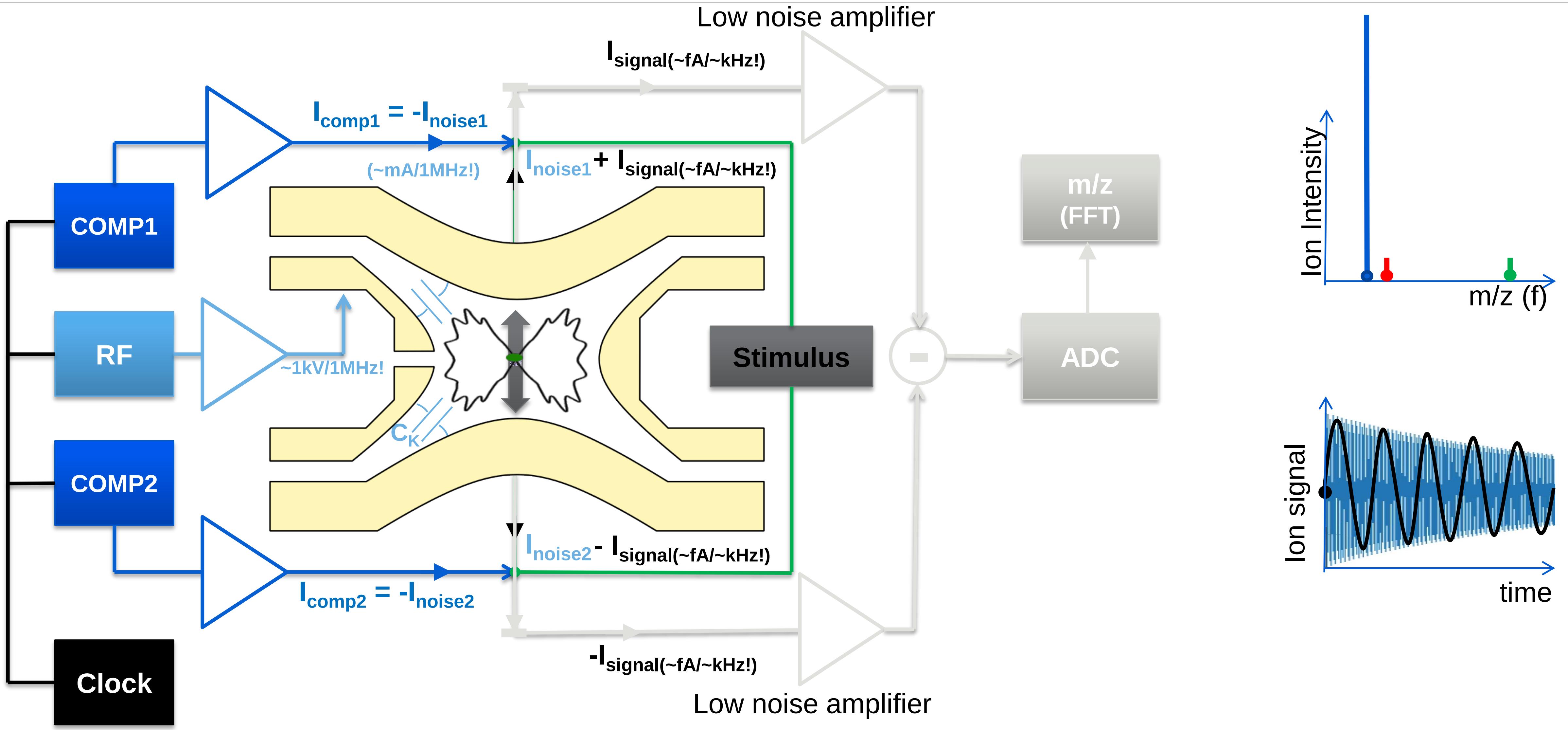
- iTrap allows endpoint detection of etch and cleaning processes
  - Process optimization and process time reduction

- Study of etch/movpe reaction products possible
  - As a function of pressure, concentration and previous cleaning steps to reduce e.g. first wafer effects
  - Gain insight of process chemistry

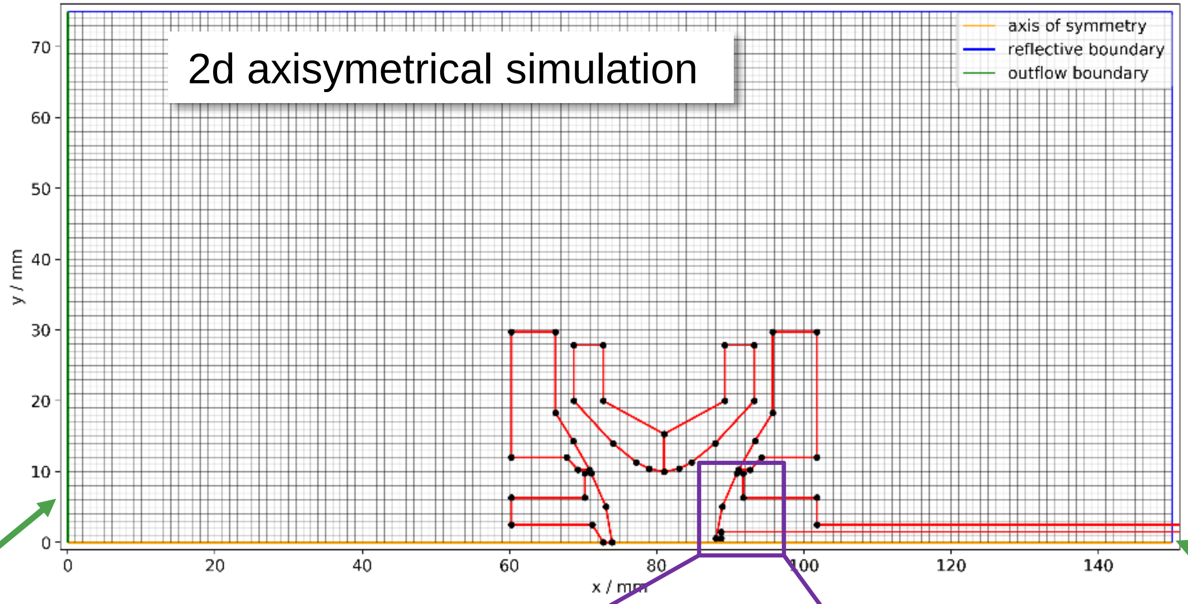
- Heavier species like $SiCl_3$, $TiCl_3$, $SiCl_4$, $HfCl_2$ can be easily monitored, also in non-plasma conditions (when OES cannot be used)

ZEISS

Fourier Transform Ion Trap mass spectrometer

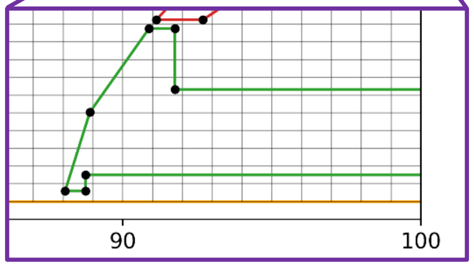


DSMC Simulation



outflow boundary (“pump”):
emit/face subsonic

→ At the boundary layer, particles are introduced into the simulation box to match the pressure.



Gas inlet

25