Using Multi Way PCA (MPCA) for Advanced Monitoring and Diagnosis for Plasma Processing based on Optical Emission Spectroscopy

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Outline

- Introduction - APC in high volume production
- Hardware integration and software structure
- Data reduction by PCA
- Experiments
  - Contact etch at AMAT MxP+
  - Poly etch at AMAT DPS
- Summary and outlook

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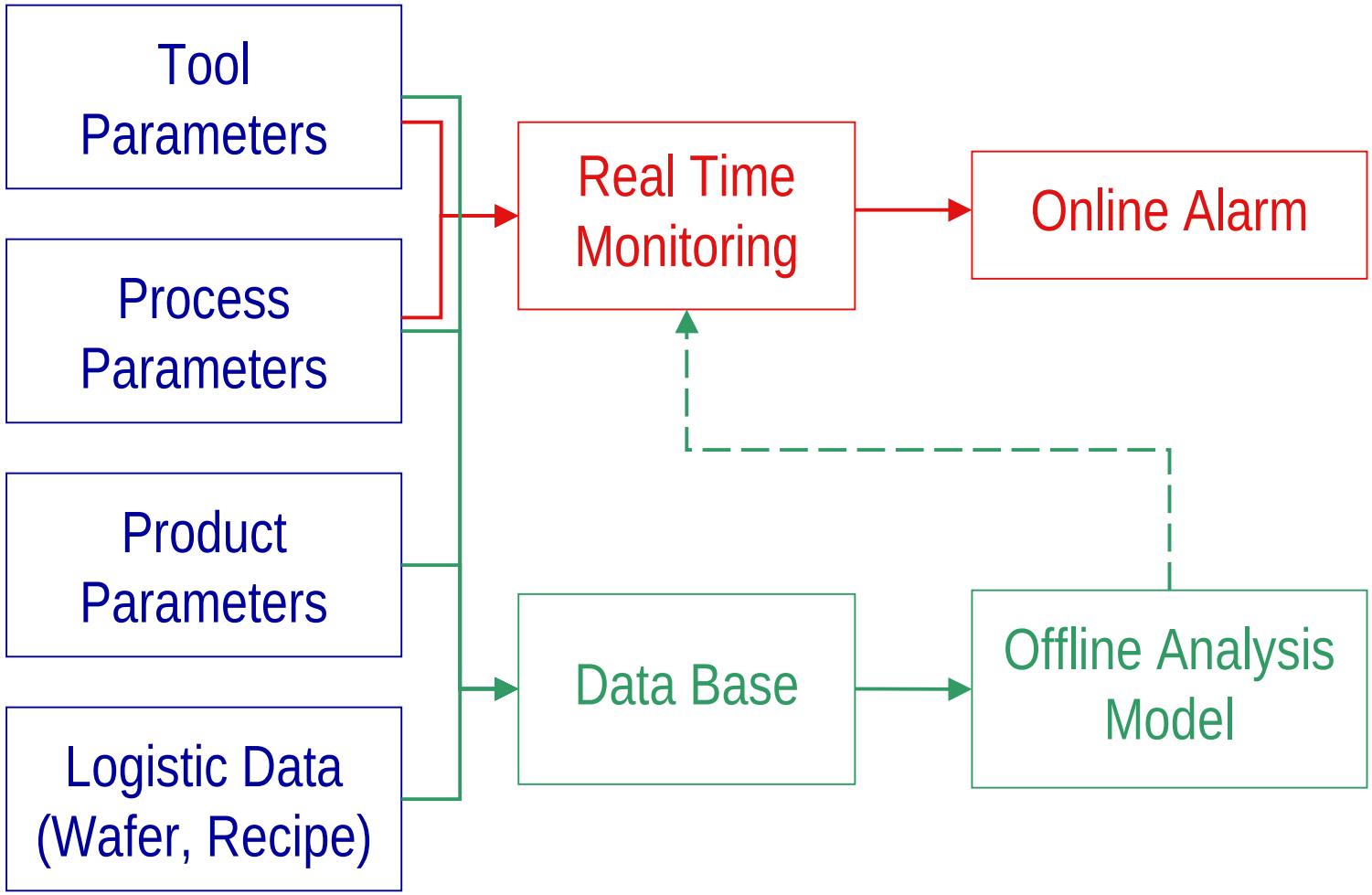
APC - offline analysis and real time process control including alarms



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Data reduction – an essential need for APC in high volume production

- APC in high volume production creates large amounts of data
- Data reduction is an essential need for off line analysis and real time process monitoring
- Methods for data reduction:
  - Measurement techniques based on physical models
  - Calculation of statistical key numbers
  - Use of complex process parameters
  - Model based data analysis

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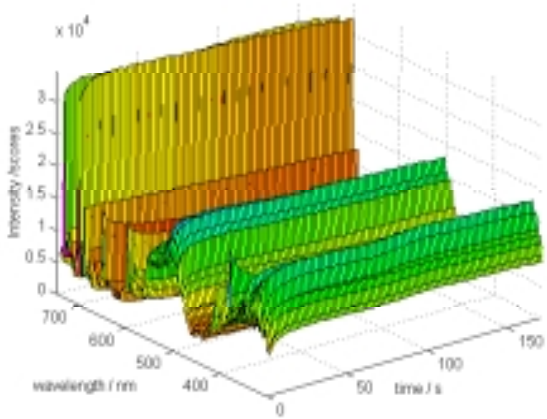
Features of Hamamatsu MPM spectrometer



- Spectral range: 200 - 950 nm
- Resolution: < 2 nm
- CCD line channels: 1024
- Connection to Host PC
  via TCP-IP, RS 232
- Internal data processing for endpoint detection; up to 100 endpoint scrip‘s are available
- Digital / analog port‘s for connection to tool

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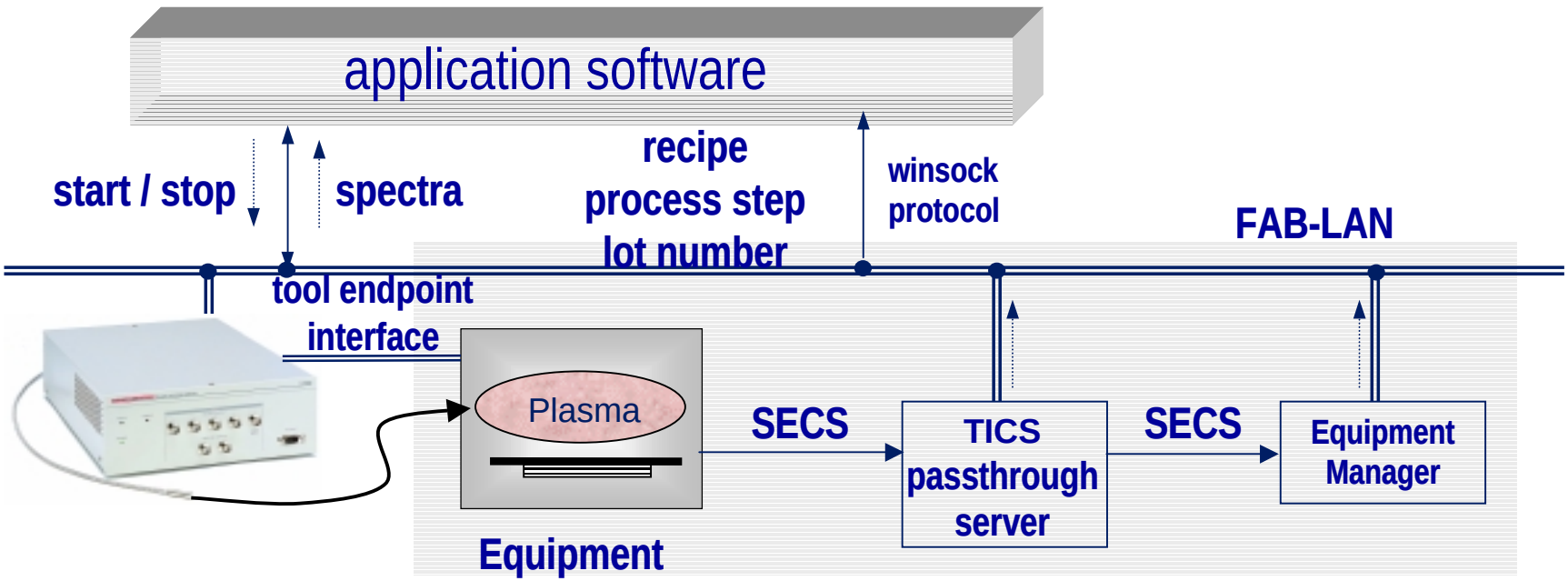
Integration of Hamamatsu MPM spectrometer



- Tool interface for stand alone endpoint detection
- Interface for logistic data
  e.g., lot and wafer number, recipe, step number

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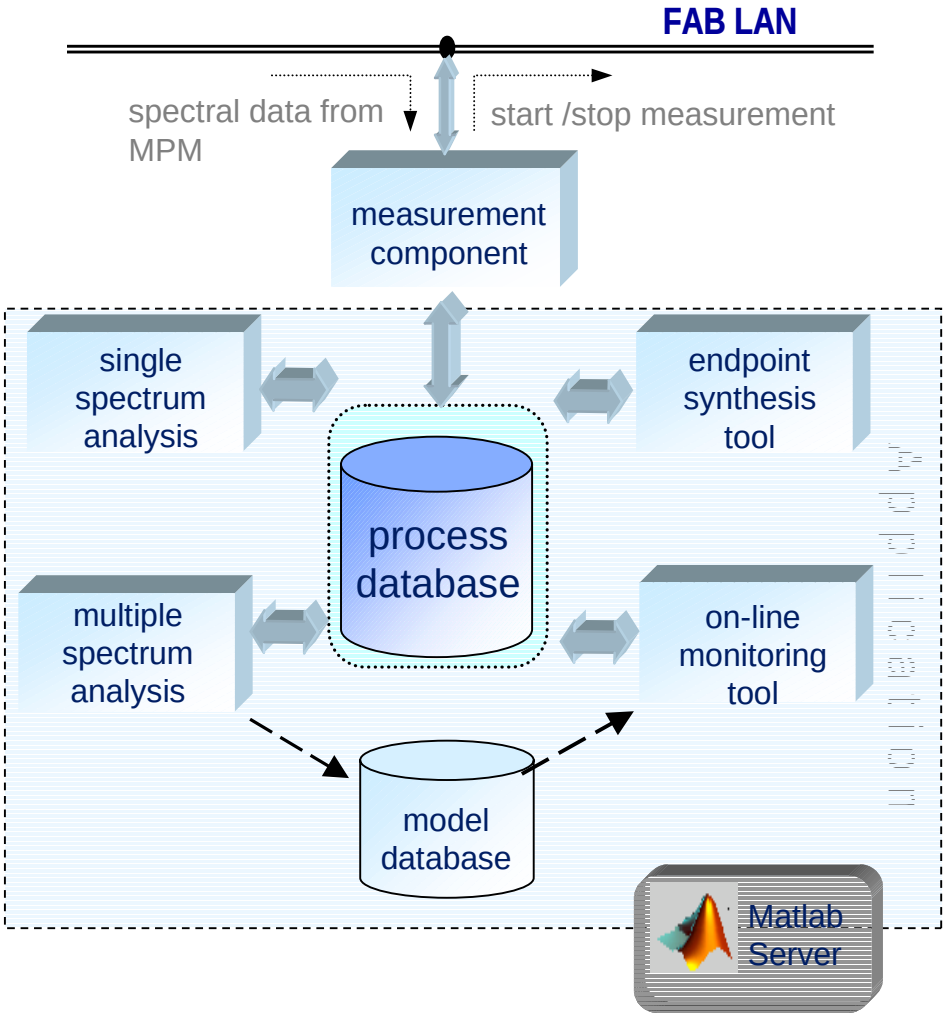
Software solution developed by Fraunhofer Institut IVI Dresden



- Database oriented spectra storage and SQL- based data access for:
  - Data visualization
  - Data analysis
  - Endpoint synthesis
  - Validation of endpoint detection algorithms

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Data reduction by key number calculation with PCA

- Simple key number extraction:
  mean, standard deviation, max, min, ...
- Extraction of key numbers using signal decomposition:
  - Tschebyscheff functions
  - Adjusted signal base (PCA)
    Multivariate key number extraction -- Multi Way PCA
- Adaptation of a nonlinear parametric signal model
- Compromise between efficiency and effort / a-priori knowledge

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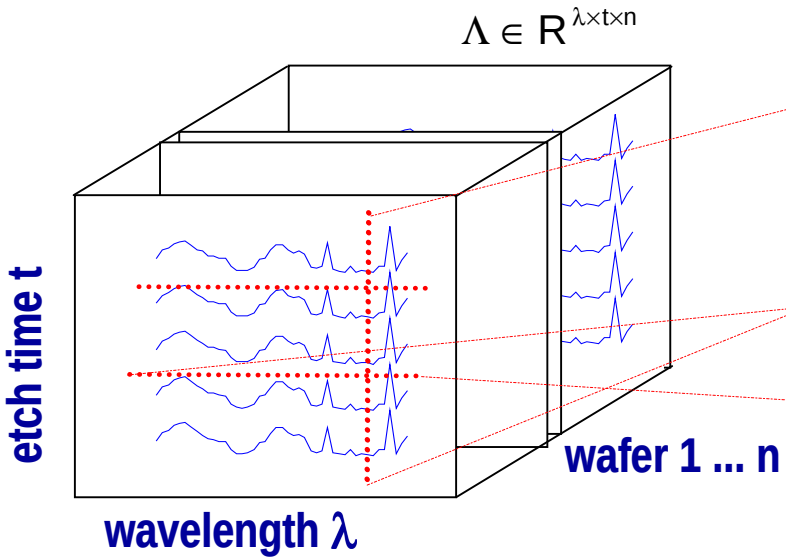
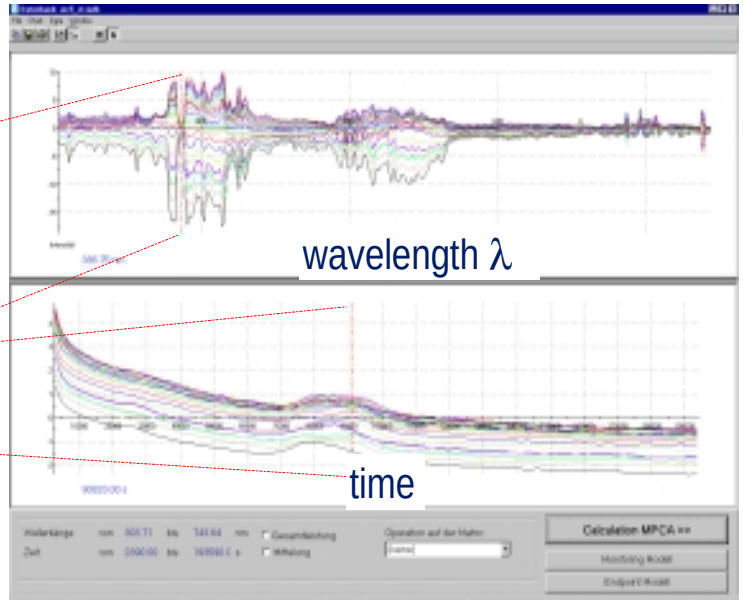
Principle of PCA – Data cube

Data cube
containing spectra

Vertical and horizontal cut
through Data cube





- Optical spectra visualized as a „Data cube“
- Optical emission spectroscopy creates very large amounts of data !

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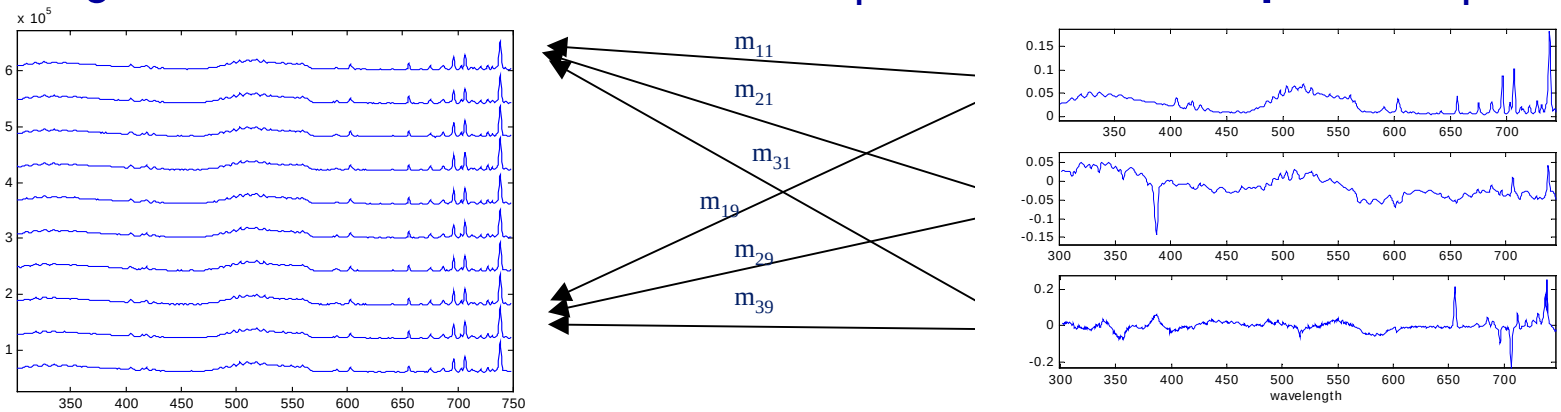
Principle of PCA – Matrix calculation

- Split of the original data matrix into orthogonal pattern u_i and orthogonal scores m_i:

$$X = M \cdot U^T = \sum_i m_i \cdot \underline{u}_i^T$$

- Scores represent the weight of the corresponding pattern in the original data sample

original data: X **scores: m_i** **base pattern: u_i**



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Application of PCA on DRAM contact etch at Applied Materials MXP+ chamber

- Contact etch at Applied Materials MxP+ chamber
- Standard oxide etch chemistry, CF_4, CHF_3, Ar
- Observation of 5 wet clean cycles (WC), about 4000 wafers
- Simple process mix, two different recipes for two high volume DRAM products mainly

Step	**Product 1**	**Product 2**
Descum	--	N_2 / O_2 descum
Main etch 1	BPSG etch	BPSG etch
Main etch 2	--	Nitride etch

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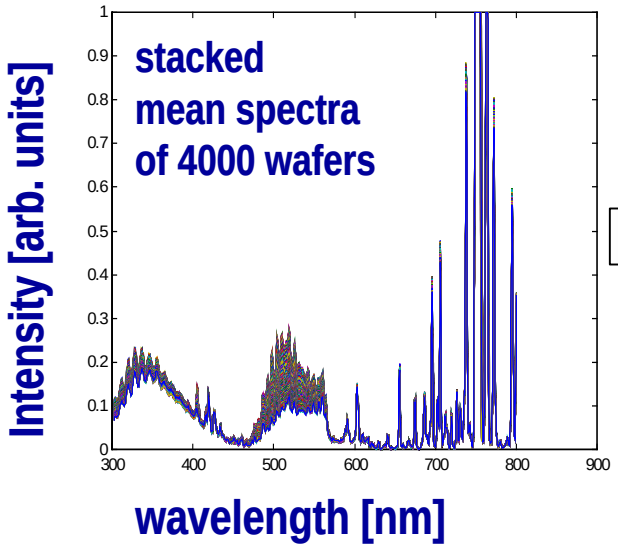
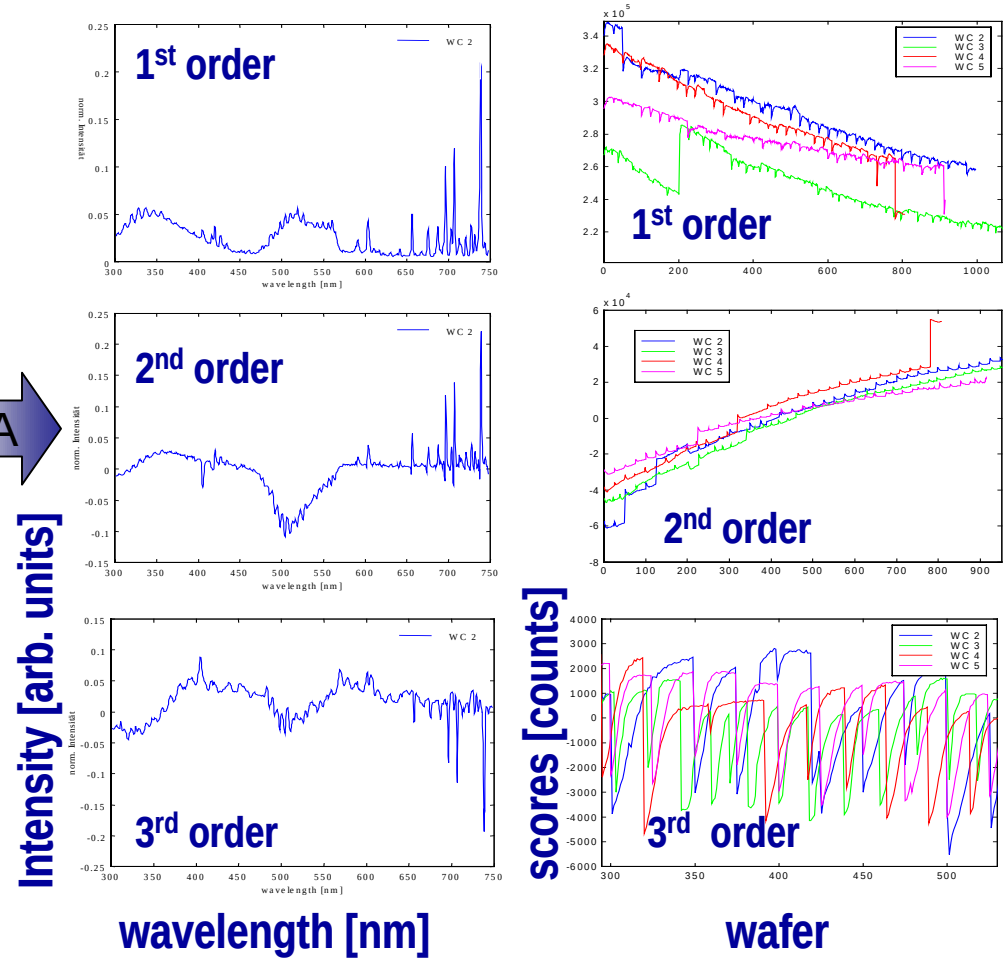
PCA results obtained on DRAM contact etch at Applied Materials MXP+ chamber

Matrix X: mean spectra
of 4000 wafers
of 5 wet clean cycles (WC)



PCA

Patterns and scores 1st to 3rd order of WC 2 .. 5



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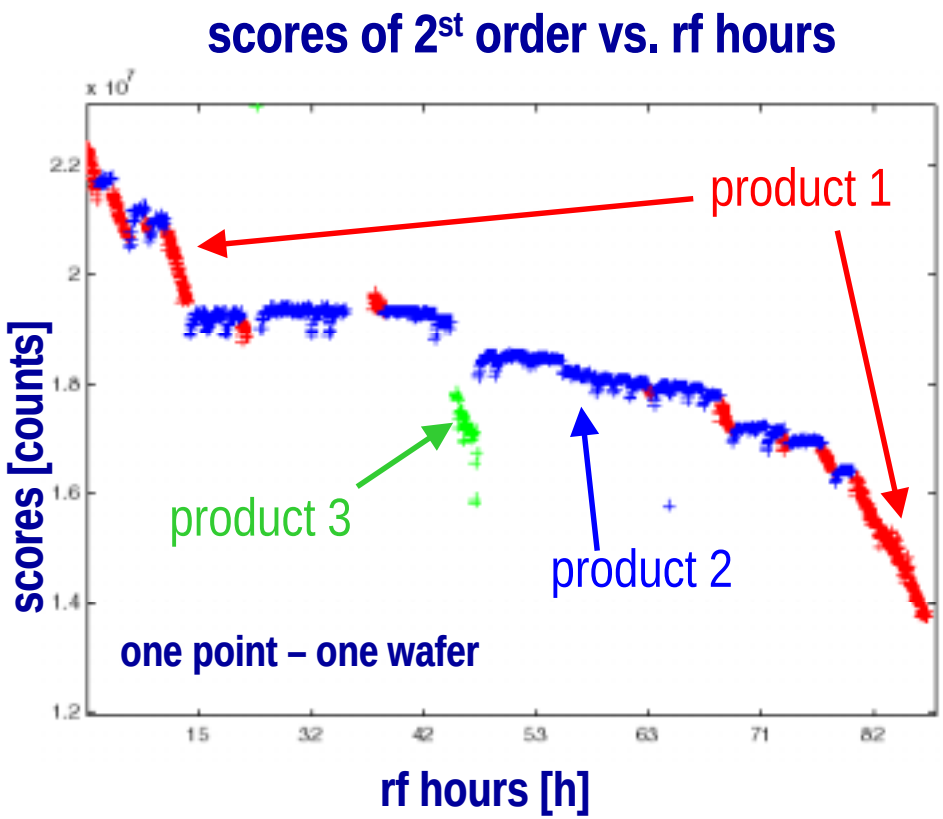
PCA results obtained on contact etch at Applied Materials MXP+ chamber, cont.

- CF_4, CHF_3, Ar chemistry, two main DRAM products
- Scores of 2st order of the first observed at wet clean cycle 1



- Product 1: high polymerizing
  Product 2: low polymerizing
- Scores of 2st order decrease during WC1, caused by:
  - Increasing light absorption at polymer layer on the recess side window
  - And real process drift caused by polymer on chamber wall
- Product dependent monitoring of chamber condition

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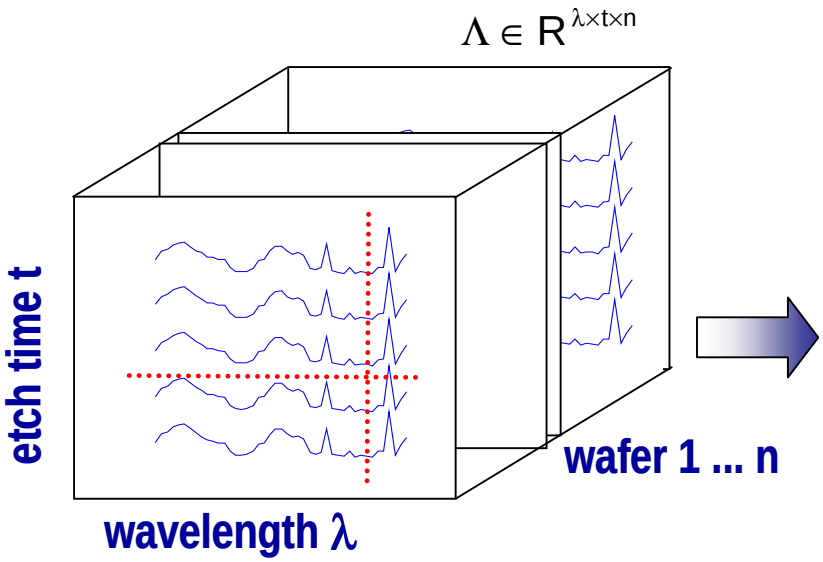
Multi-Way Principle Component Analysis



$$\sum_i \sum_j M(i,j,n) \cdot u_i(\lambda) v'_j(t)$$

for $n = 1,\ldots,N$

- "One way PCA": use of <u>one mean spectrum</u> per wafer
- Multi Way PCA: Calculation of orthogonal wave pattern u_i and orthogonal base time signals v_i by unfolding the original data cube in <u>time and wave</u> direction

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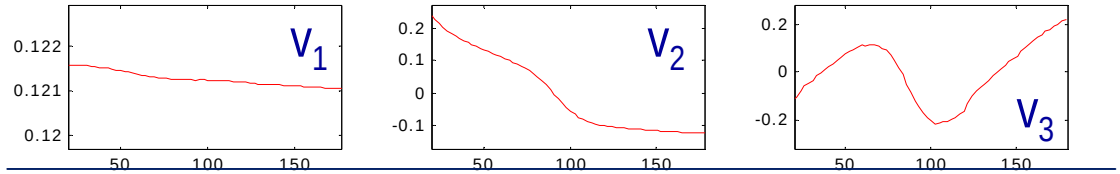
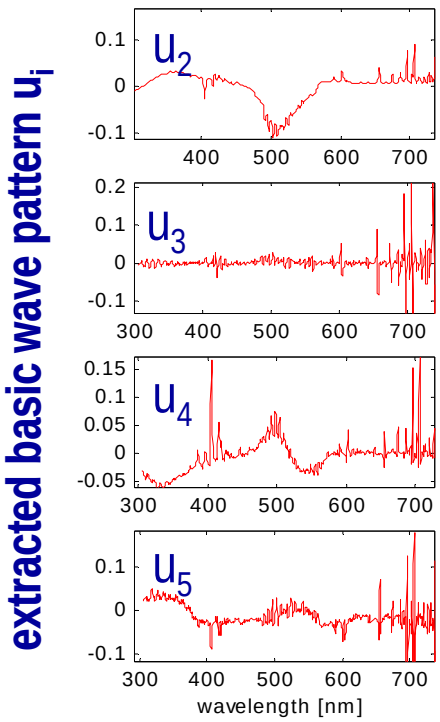
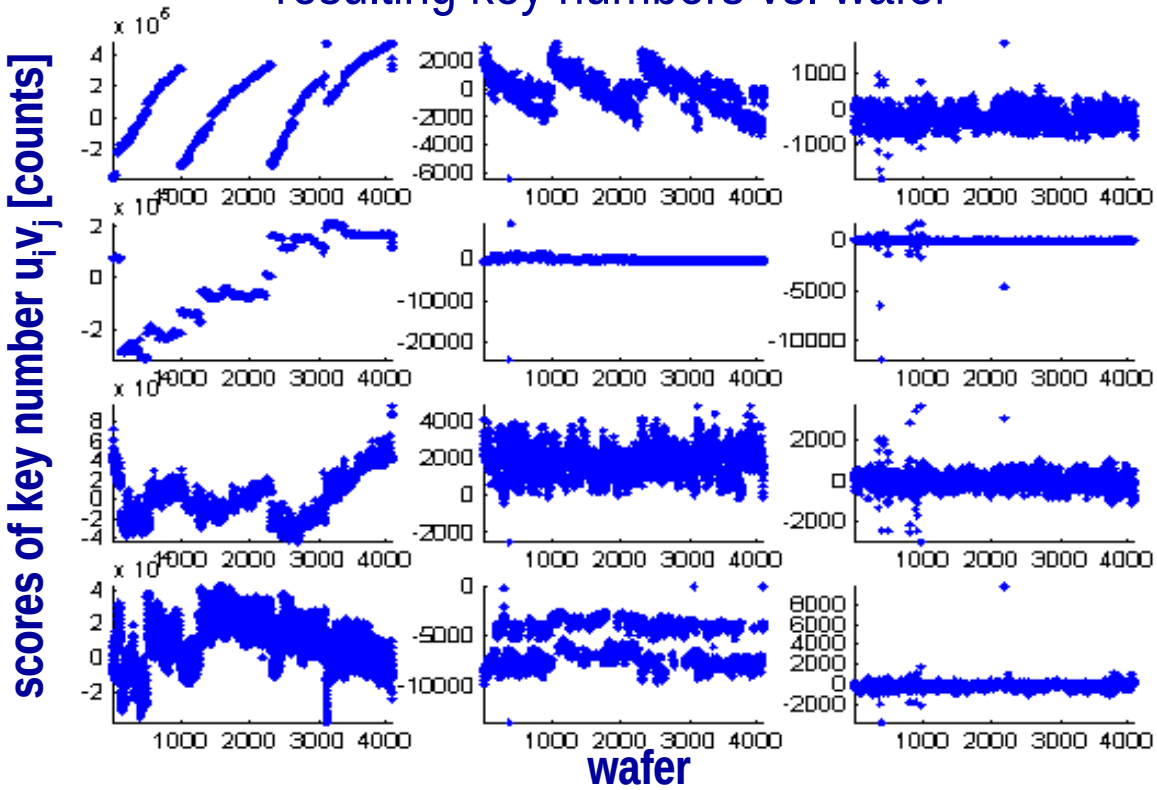
Some examples of key numbers obtained by Multi Way PCA on contact etch at AMAT MxP+

extracted basic time signals v_j





resulting key numbers vs. wafer



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Interpretation of key numbers u_i;v_j

- Significant signatures up to 10th…20th order of u_i and v_j, max. about 100...400 key numbers
- Significant key numbers limited by:
  - increasing order decreasing information content
  - redundant signatures

- PCA = mathematical algorithm, no physical or technological input
- Advantage: universal, application to any kind of data possible
- Disadvantage: no clear physical meaning of these key numbers
- Difficult interpretation

- Interpretation of key numbers with help of:
  - Physical, chemical, technological knowledge
  - Comparison to other measurement techniques, delivering physical parameters

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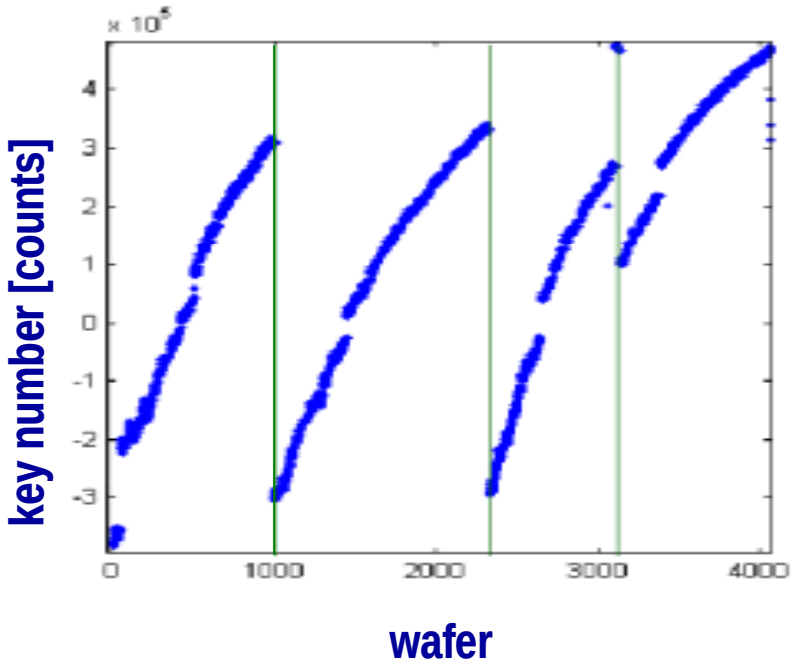
Interpretation of optical key numbers with experience

key number $u_2;v_1$ vs. wafer



- Key number $u_2;v_1$ shows reproducible long term drift between wet cleans.
- Experience possible reasons:
  - Light adsorption by polymer, growing on recess side window
  - Drift of gas composition, caused by polymer on the chamber walls
- No influence of power dissipation here

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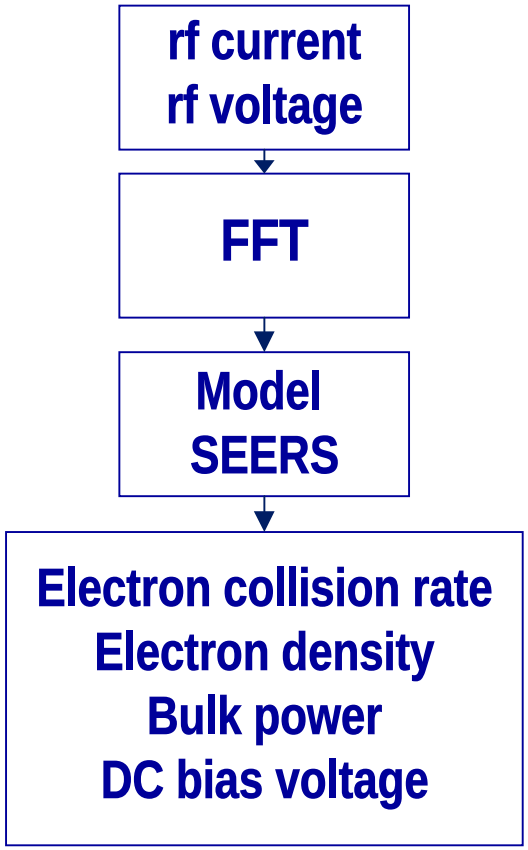
Reference: Plasma parameter measurement with SEERS



- SEERS = **S**elf **E**xcited **E**lectron **P**lasma **R**esonance **S**pectroscopy
  = „electrical“ plasma measurement technique
- Measurement of:
  - rf current
  - rf voltage
- Real time calculation of plasma parameters:
  - Electron collision rate [collisions per sec]
  - Electron density [electrons per cm^3]
  - Bulk power [mW per cm^2]
  - DC bias voltage [V]
- Plasma monitoring system HERCULES, based on SEERS was used as reference system

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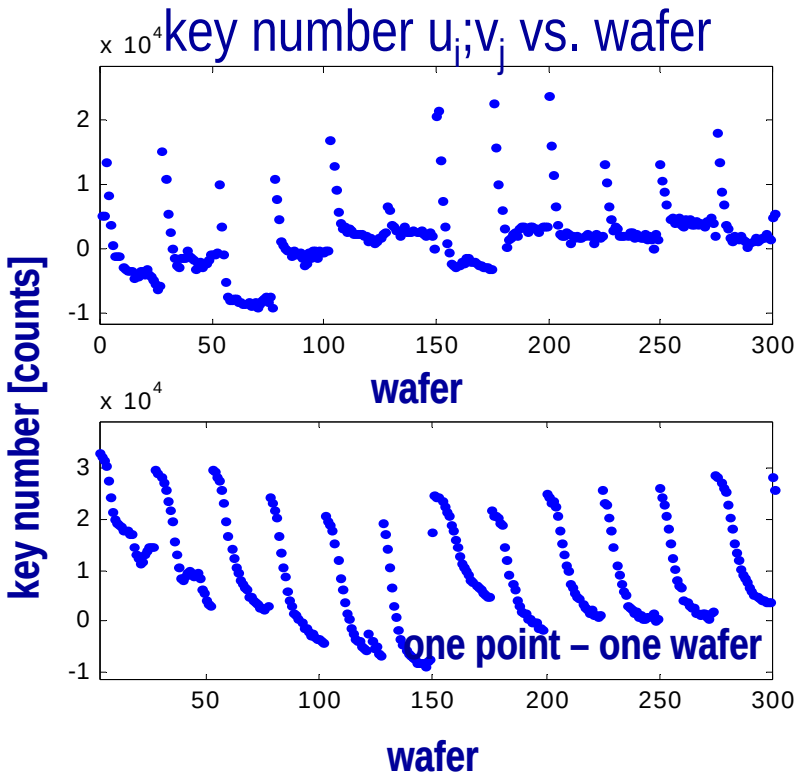
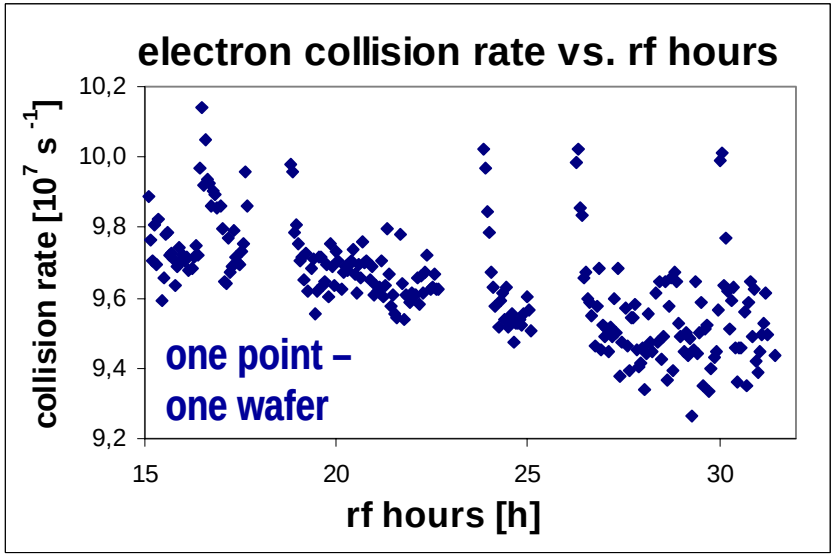
Interpretation of optical key numbers with comparison to plasma parameters



- Short term drift indicated by:
  - Optical key numbers, e.g., u_4;v_1, u_5;v_1
  - Electron collision rate



- Possible reasons:
  - Temperature drift
  - Gas adsorption and desorption

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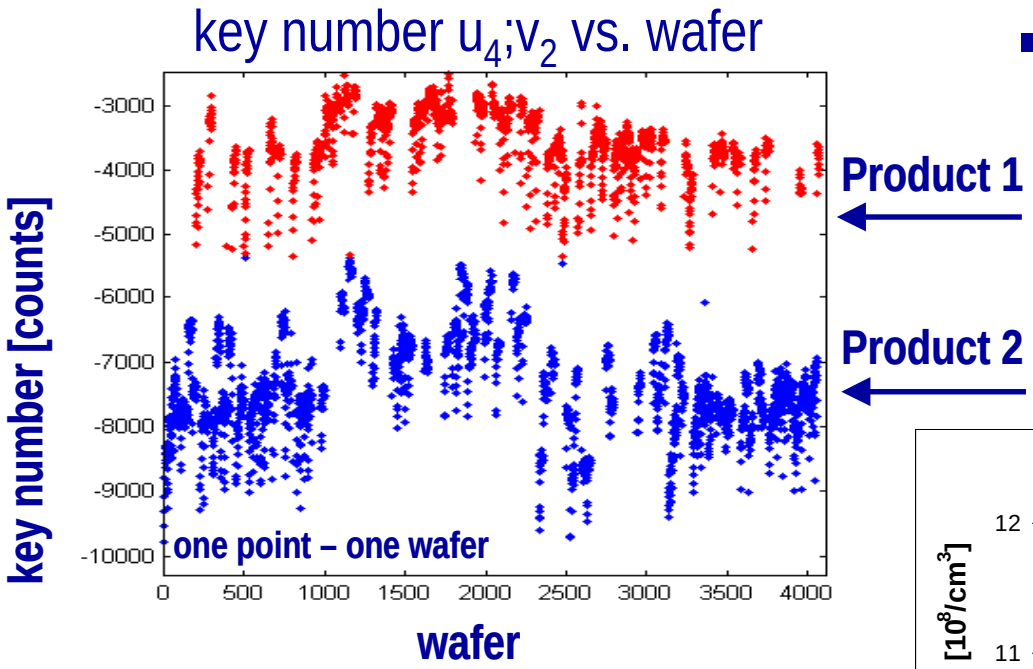
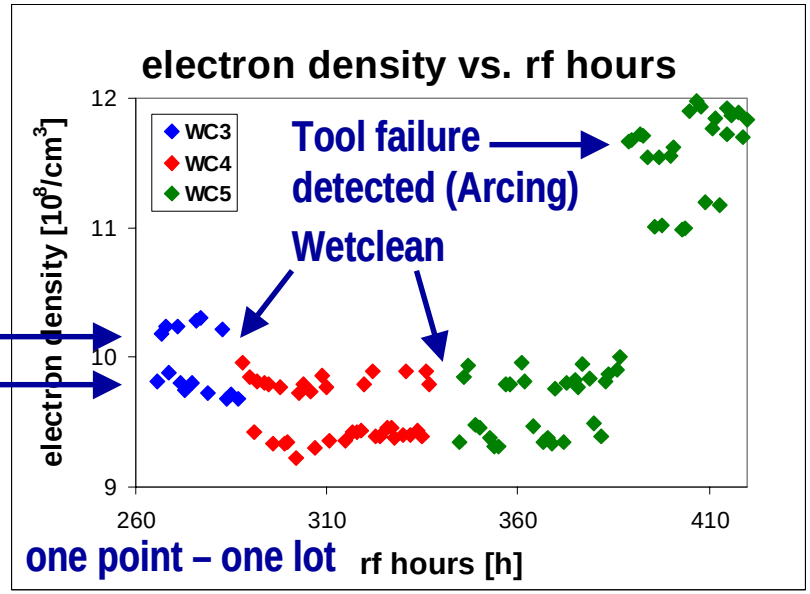
Interpretation of optical key numbers with comparison to plasma parameters, cont.



- Product indicated by:
  - Optical key number $u_4;v_2$ (no optical measurements available during the tool failure)
  - Electron density



- Reason:
  - Different open area of 2 products

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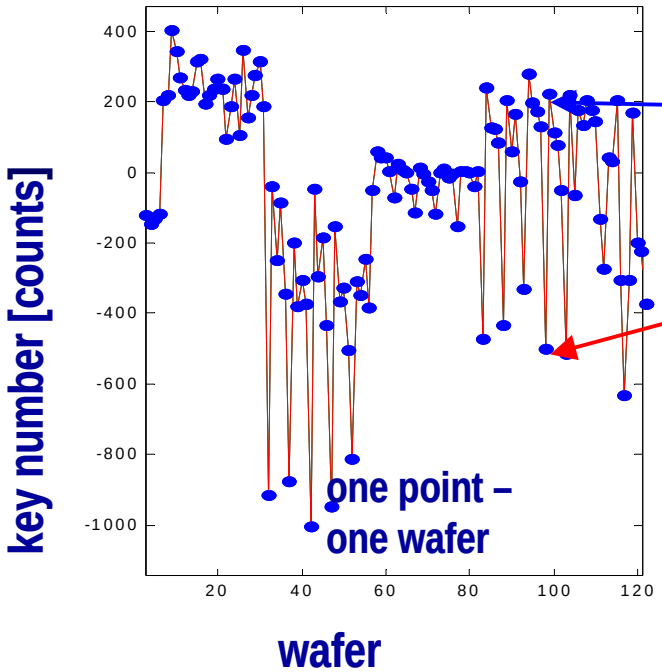
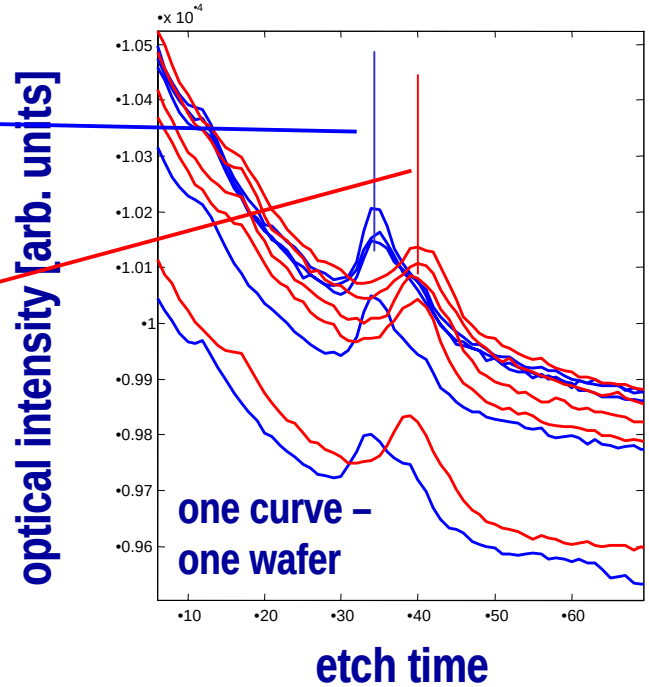
Interpretation of optical key numbers with comparison to endpoint signatures

key number $u_5;v_6$ vs. wafer



optical endpoint signal vs. etch time



- Key number $u_5;v_6$ corresponds with endpoint time
- Superimposition of previous processes, depending on lot

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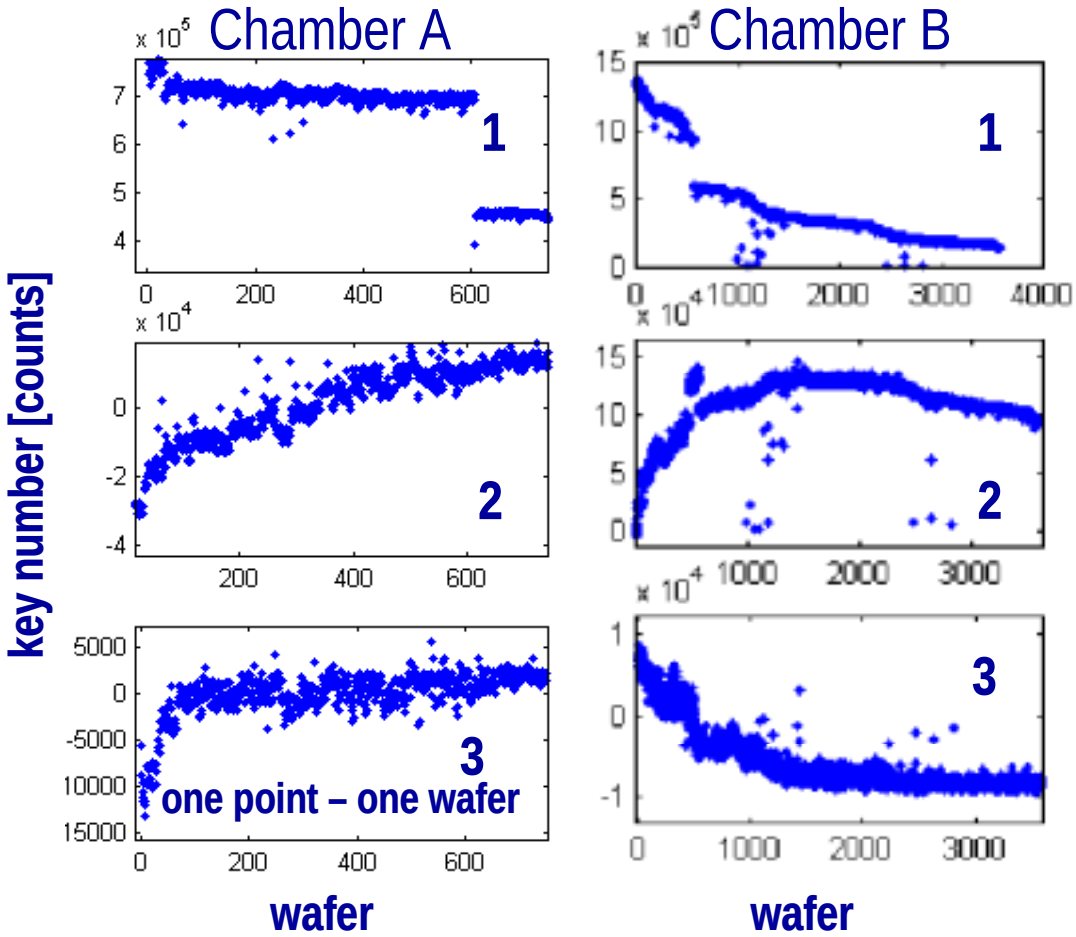
Topical Example: Chamber comparison at poly recess etch in Applied Materials DPS

key numbers vs. wafer



- Measurement at chamber B several weeks later.
- Key numbers indicate other conditions at chamber B (see 3).
- Reasons not yet identified.

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Summary and outlook

- PCA / MPCA is a universal mathematical method for data analysis and data reduction.
- Key numbers obtained by application of PCA / MPCA on optical spectra are complex process parameters, indicating tool and wafer impacts.
- Interpretation of key numbers is possible by use of:
  - extracted spectral wave pattern and basic time signals
  - physical, chemical, technological knowledge
  - comparison to other process parameters and tool parameters
- Actual evaluation / application status:
  - Endpoint detection demonstrated at contact etch processes
  - Application for optimization of endpoint signals and clean processes
- Use for real time process control in high volume production is a great challenge, due to large number of key numbers and complex interpretation.

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