Thermal Wave Analysis of Implanted Layers in Semiconductors: Measurement Performance vs. Process Requirements

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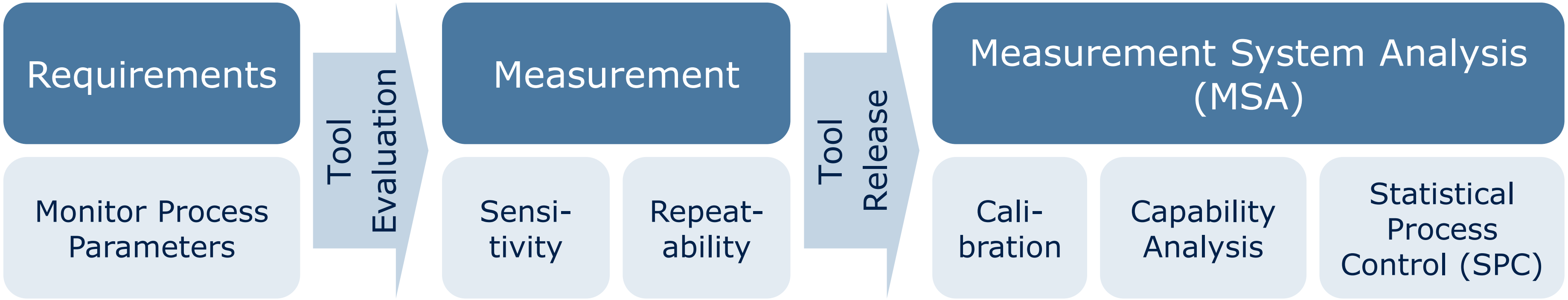
Outline

- Introduction
- Thermal Wave Analysis
  - Theory
  - Results
- Measurement System Analysis (MSA)
  - Capability analysis
- Summary & Outlook

Introduction



Requirements

Monitor Process Parameters

Tool Evaluation

Measurement

Sensi-tivity

Repeat-ability

Tool Release

Measurement System Analysis (MSA)

Cali-bration

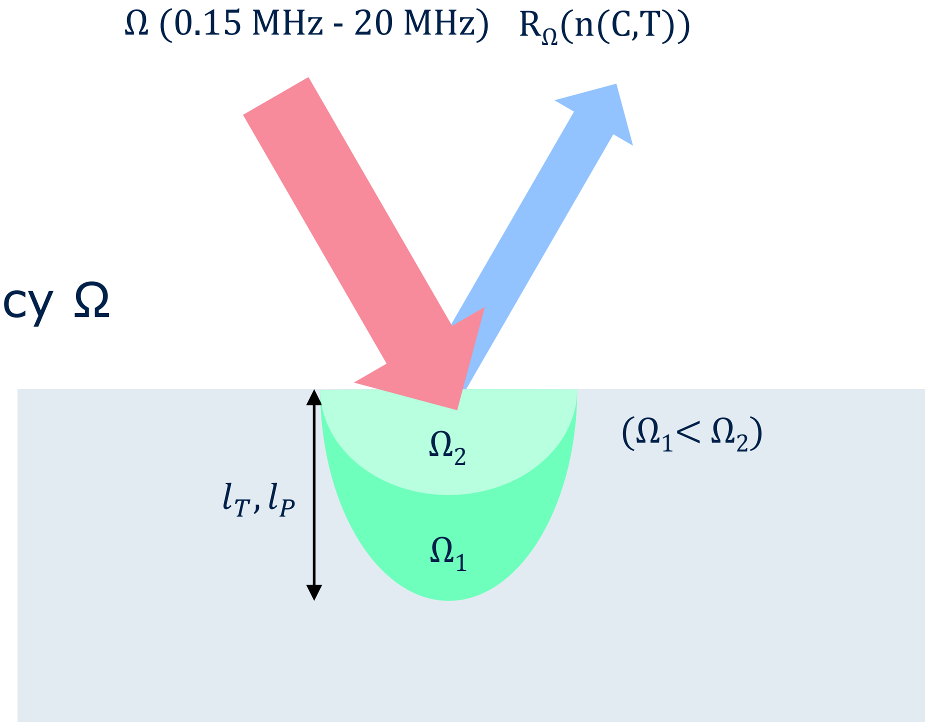
Capability Analysis

Statistical Process Control (SPC)

- Measurement of implant dose (TWIN SC4 system (PVA Metrology and Plasma Solutions GmbH)
  - Measurement directly after implantation. No post-treatment
  - Measurement on productive wafers (compared to 4PP)

Thermal Wave Analysis Theory I

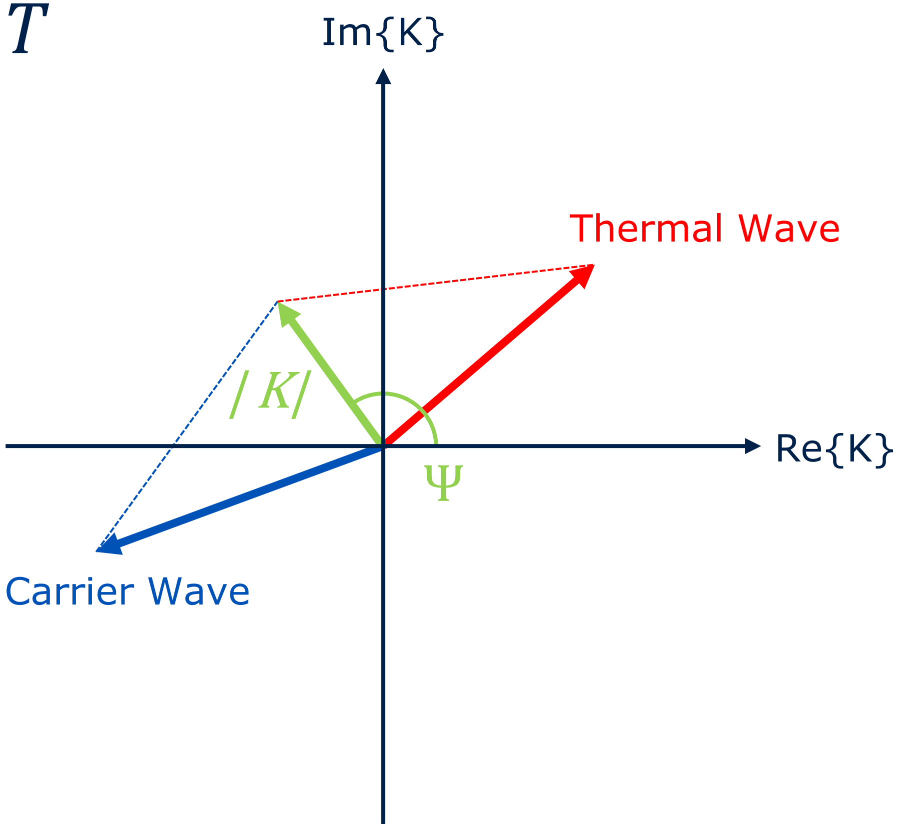
- Excitation of a sample by local absorption of photons (laser 16mW)
  - Generation of carrier wave
    - $l_P = \sqrt{\frac{2D\tau}{1+\sqrt{1+(\Omega\tau)^2}}}$
  - Generation of thermal wave
    - $l_T = \sqrt{\frac{2\kappa}{\Omega}}$
  - Tunable modulation frequency Ω



- Detection of reflected light
  - Refractive index n(C,T)

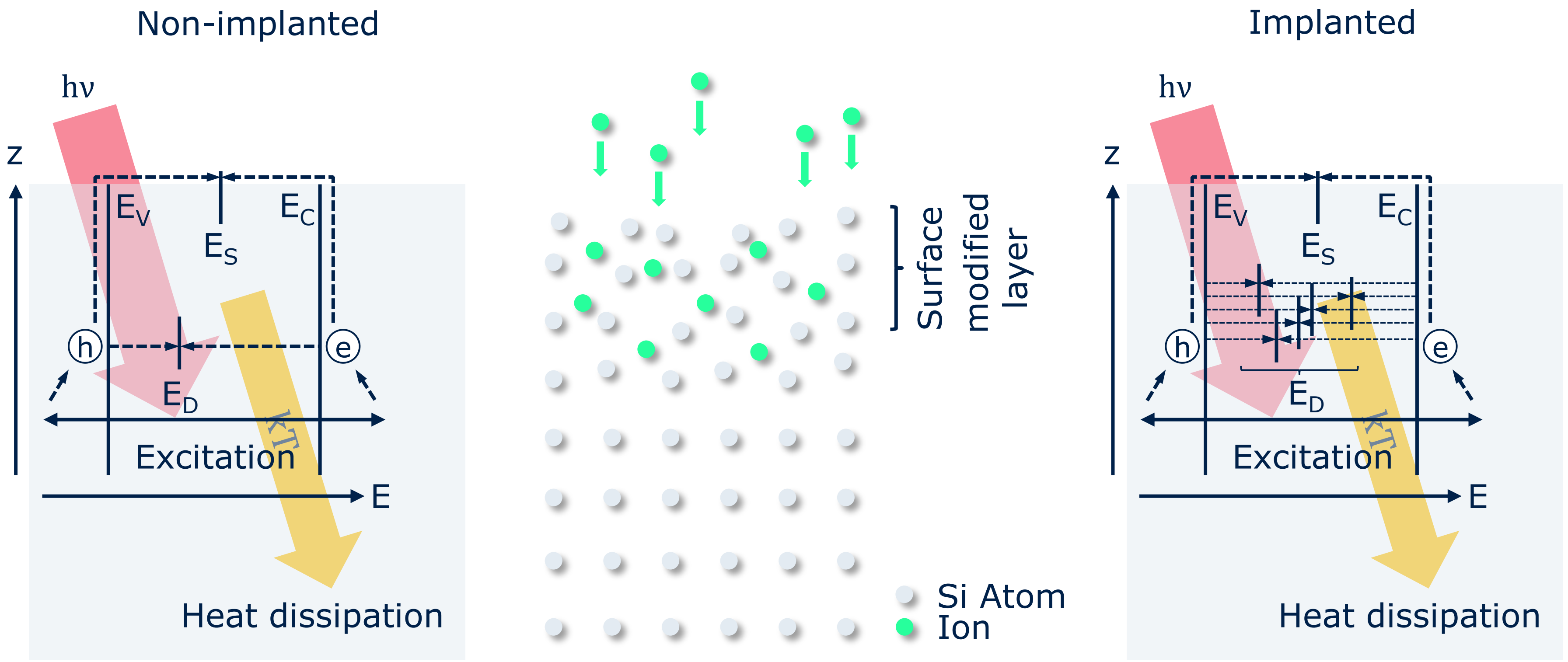
Thermal Wave Analysis Theory II

- Photothermal response
  - Complex conversion coefficient K
  - Superposition of carrier and thermal wave
  - $$K = \frac{1}{R} \cdot \frac{\delta R}{\delta c} \cdot \hat{C} + \frac{1}{R} \cdot \frac{\delta R}{\delta T} \cdot \hat{T}$$



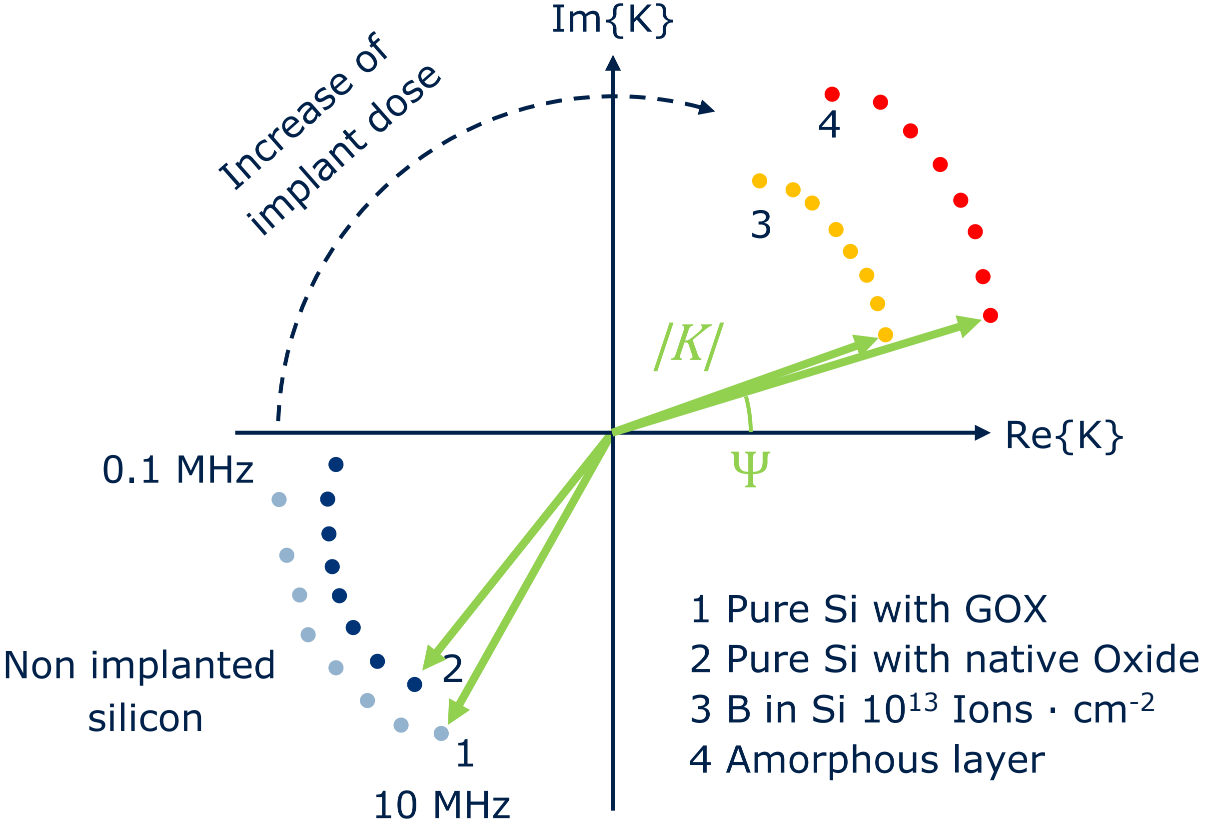
Thermal Wave Analysis Theory III

- Effect of implantation on carrier and thermal wave



Thermal Wave Analysis Theory IV

- Excitation → CARRIER WAVE → recombination → THERMAL WAVE → heat dissipation

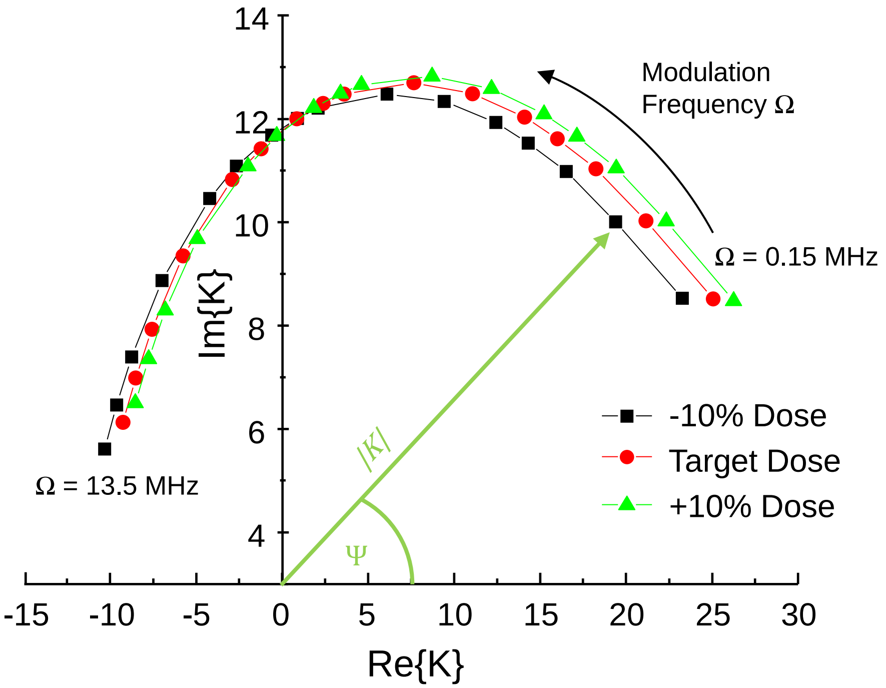


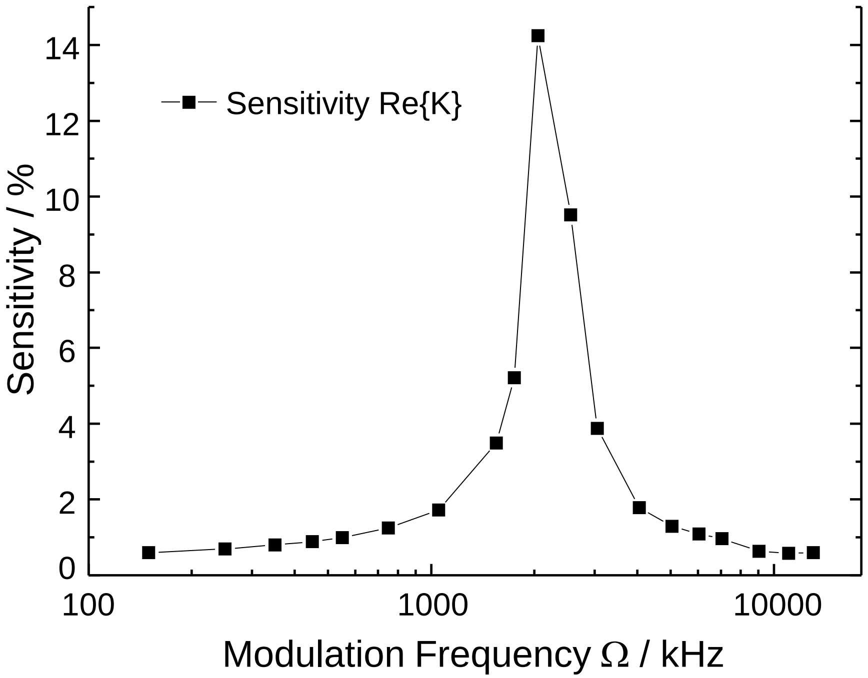
1 Pure Si with GOX
2 Pure Si with native Oxide
3 B in Si 10^{13} Ions · cm^{-2}
4 Amorphous layer

Optimization of Dose Measurement Parameters - Sensitivity

- Conversion coefficient $K(\Omega)$
  - Amplitude $|K|(\Omega)$, $\Psi(\Omega) \rightarrow \mathrm{Re}\{K\}, \mathrm{Im}\{K\}$
- Recommended procedure
  - Measurement of three wafers (variation of implant dose)
  - Measurement with 19 different modulation frequencies (0.15 MHz – 13.05 MHz)
- Boron implanted wafers. Dose of $d \approx 10^{11}$ ions · cm^{-2}, implantation energy $E \approx 160 - 180$ keV

Optimization of Dose Measurement Parameters - Sensitivity

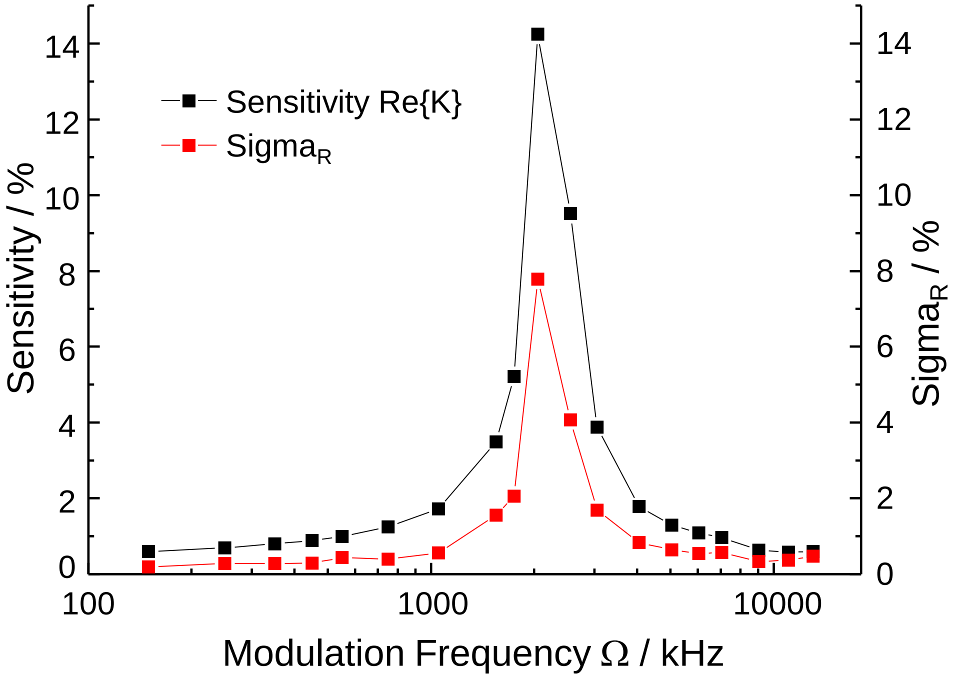




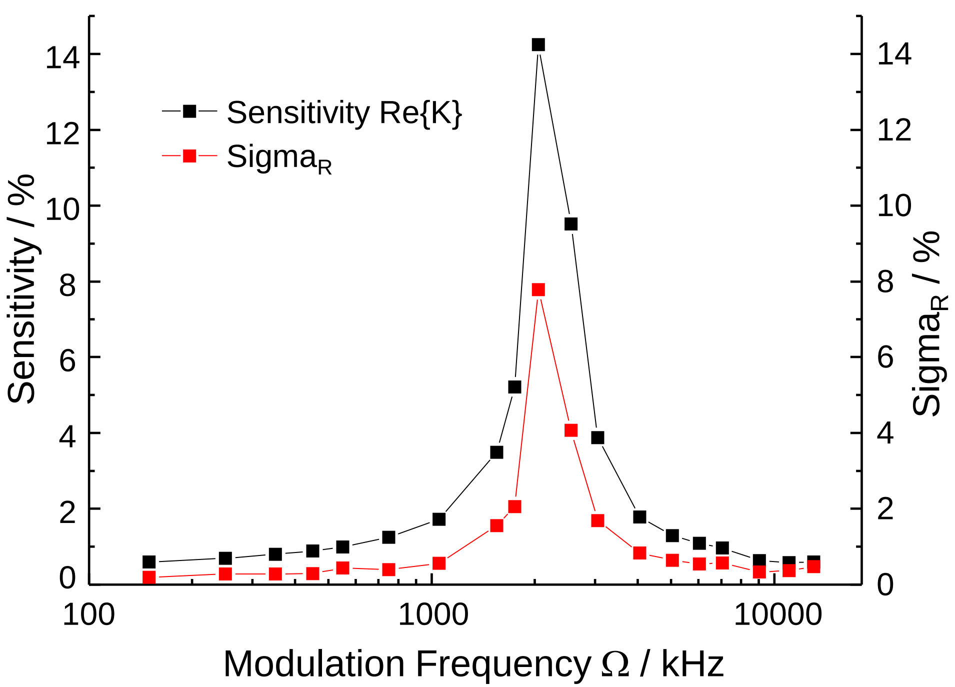
- $Re\{K\}$
- $Sensitivity = \frac{Observed\ Change}{Implemented\ Change}$
- Optimum at Ω = 2.05 MHz

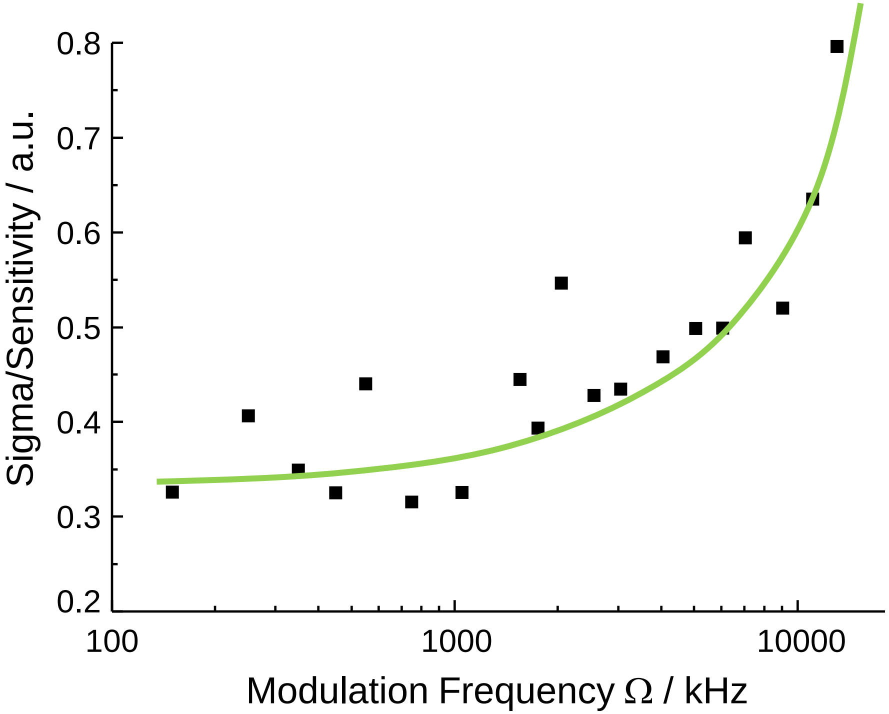
Optimization of Dose Measurement Parameters - Repeatability

- Point to point repeatability
  - Aging
  - Laser induced annealing
  - Individual measurement spots (integration time vs. micro-scans)
  - Implant uniformity
- New measurement sequence
  - 19 MP → 7125 MP

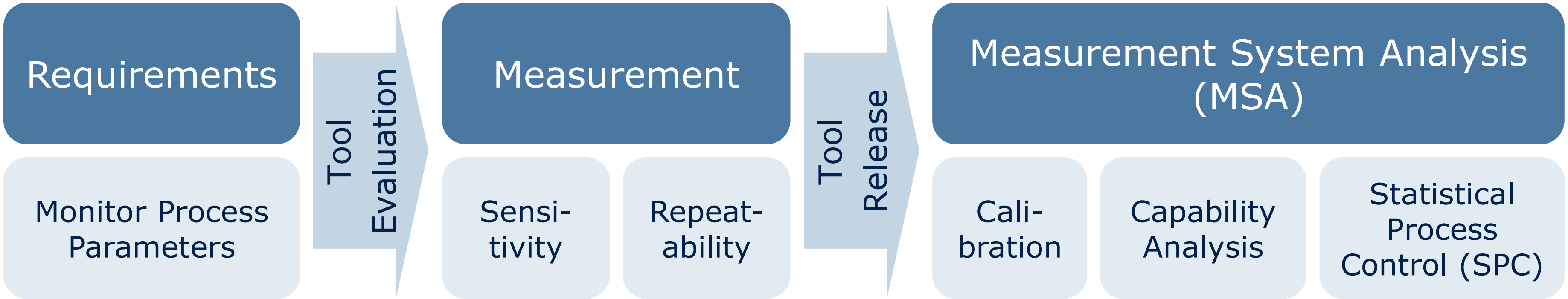


Optimization of Dose Measurement Parameters - Repeatability/Sensitivity





- Optimum at Ω = 0.75 MHz



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Tool Release

Measurement System Analysis (MSA)

- Cali-bration
- Capability Analysis
- Statistical Process Control (SPC)

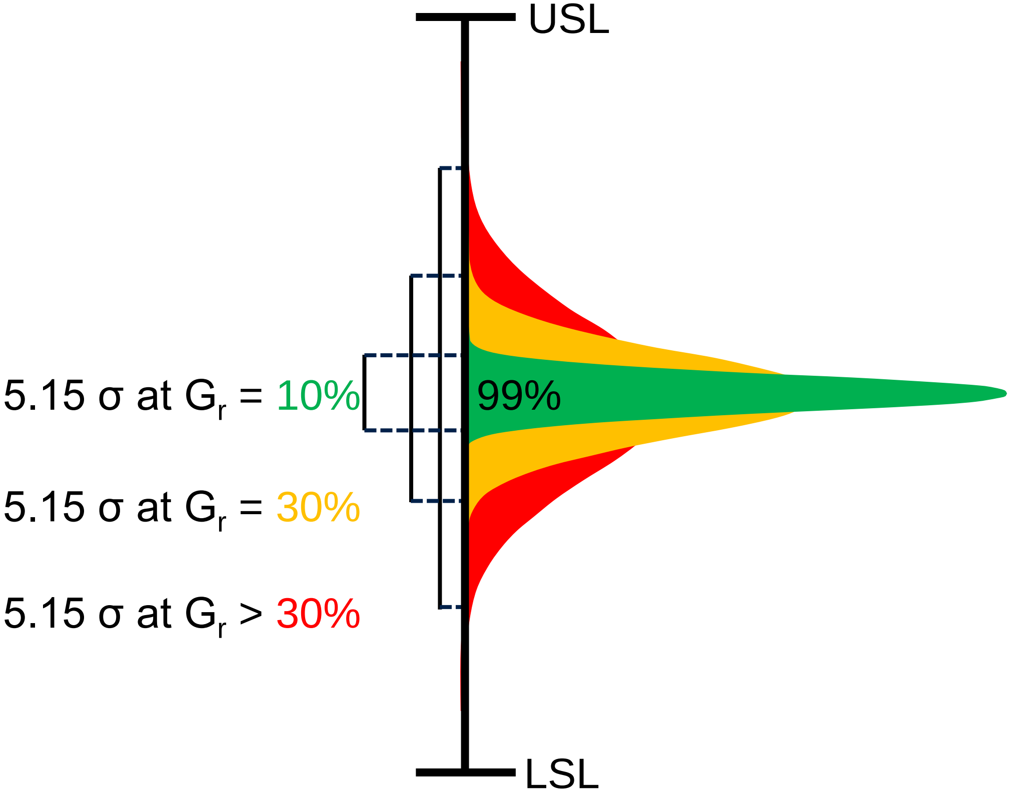
✓ ✓

Measurement System Analysis (MSA)

- Capability analysis %G_r

$$\%G_r = \frac{5.15\sigma_r}{USL - LSL} \cdot 100$$

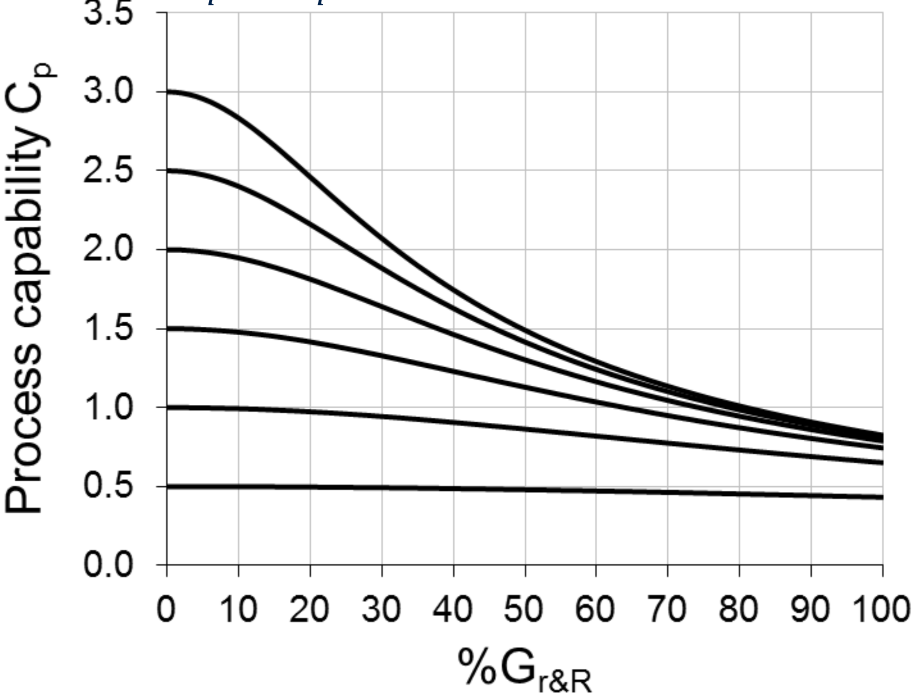
  - ☐ $G_r \leq 10\%$ capable
  - ☐ $10\% \leq G_r \leq 30\%$ conditionally capable
  - ☐ $G_r > 30\%$ incapable



Measurement System Analysis (MSA)

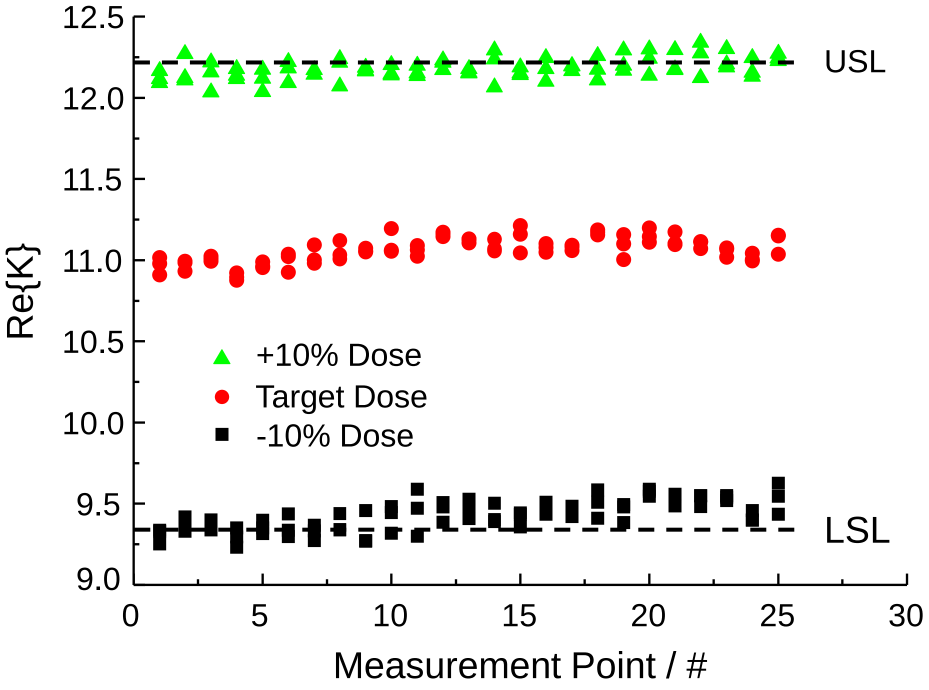
- Impact on process capability (C_p)
  - ☐ $C_p^* = \frac{USL-LSL}{6\sigma_{Process}^2}$ $\quad$ C_p^*...true process capability
  - ☐ $\sigma_{Observed}^2 = \sigma_{Process}^2 + \sigma_{Measurement}^2$
  - ☐ $C_p = \frac{1}{\sqrt{\frac{1}{C_p^{*2}} + \frac{36 \cdot G_{r\&R}^2}{5.15^2}}}$

$C_p = C_p^* \ for \ \%G_{r\&R} = 0$

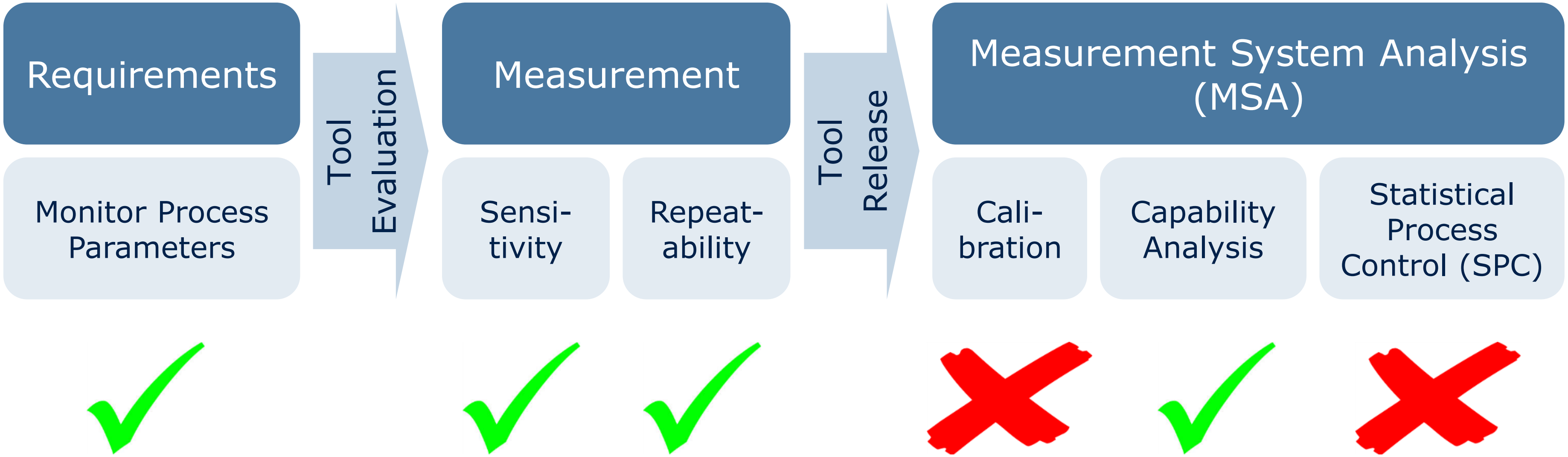


Capability Analysis
(d ≈ 10^{11} ions · cm^{-2}, E ≈ 160 - 180 keV)

- $$\%G_r = \frac{5.15\sigma_r}{USL-LSL} \cdot 100$$
  - Determination of σ_r
  - Determination of USL and LSL



Modulation Frequency / MHz	USL-LSL / Re{K}	σ_r / Re{K}	%G_r
0.75	2.8	0.4	8
2.05	2.4	0.7	14



Requirements

Monitor Process Parameters ✓

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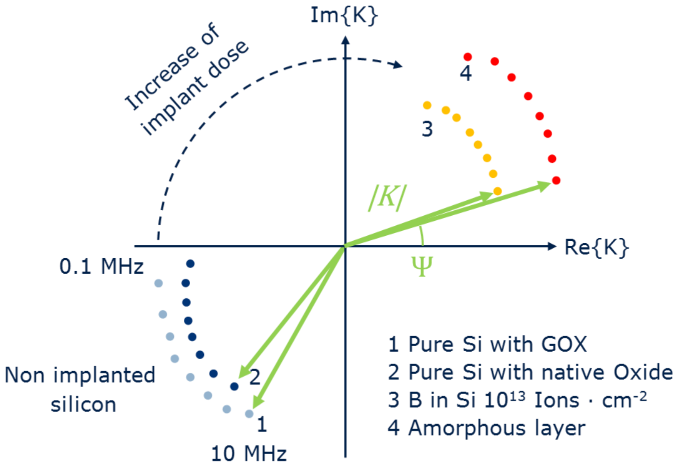
Cali-bration ✗

Capability Analysis ✓

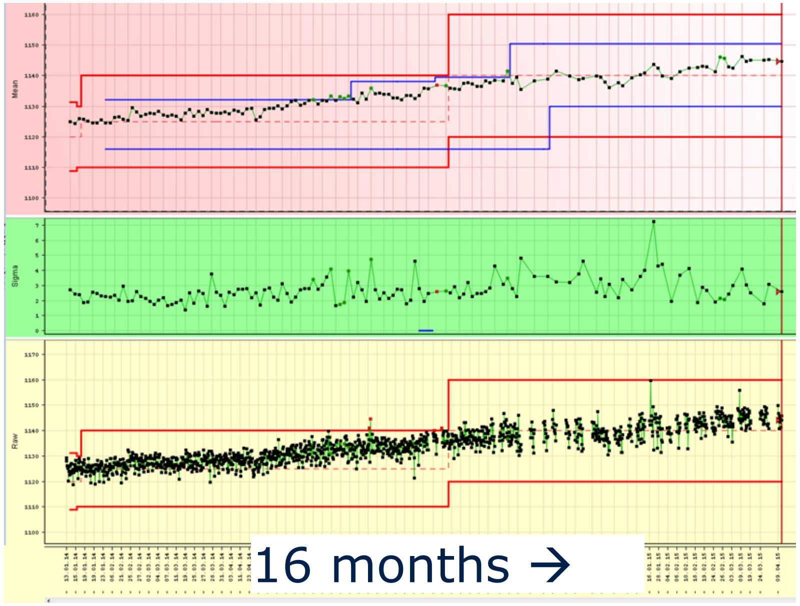
Statistical Process Control (SPC) ✗

Calibration & SPC

- Calibration Standards
  - No (stable) standard available
    - Self annealing / aging
  - Workaround GOX/Si

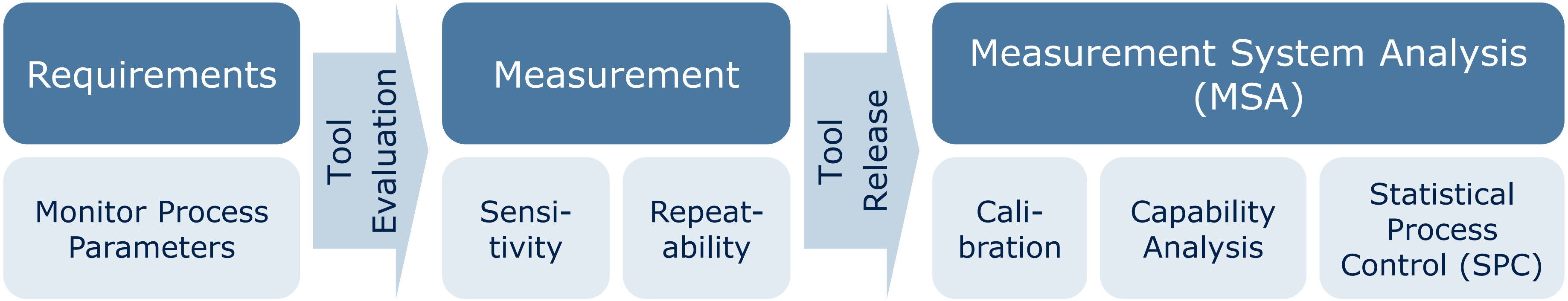


- SPC
  - No (stable) standard available
  - Workaround „ancient“ wafers
    - Problematic for new applications



16 months →

Summary & Outlook



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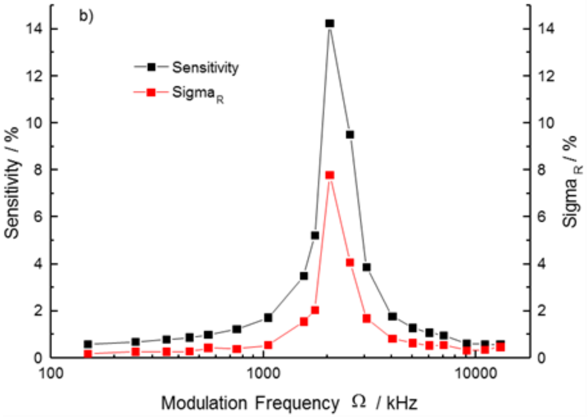
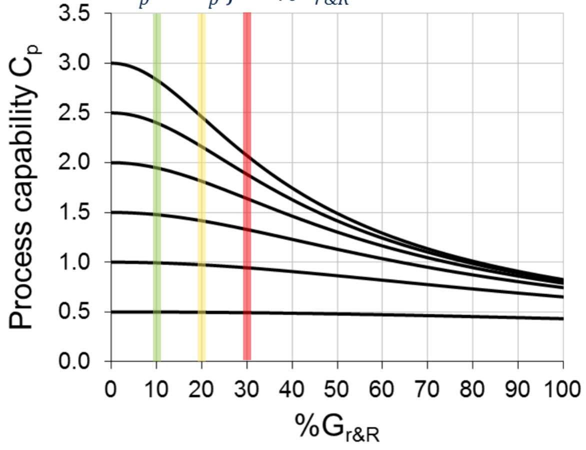
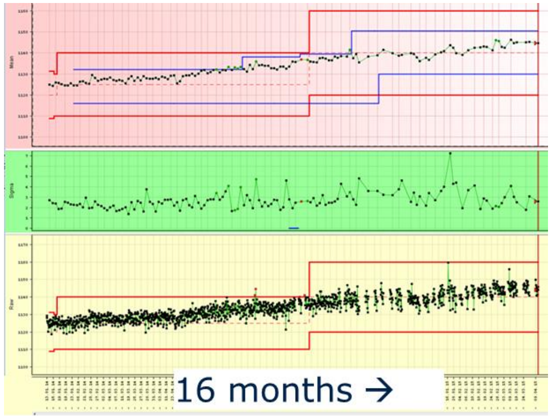


$C_p = \; C_p^* \; for \; \%G_{r\&R} = 0$





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