An innovative R2R control MIMO approach for the furnace area

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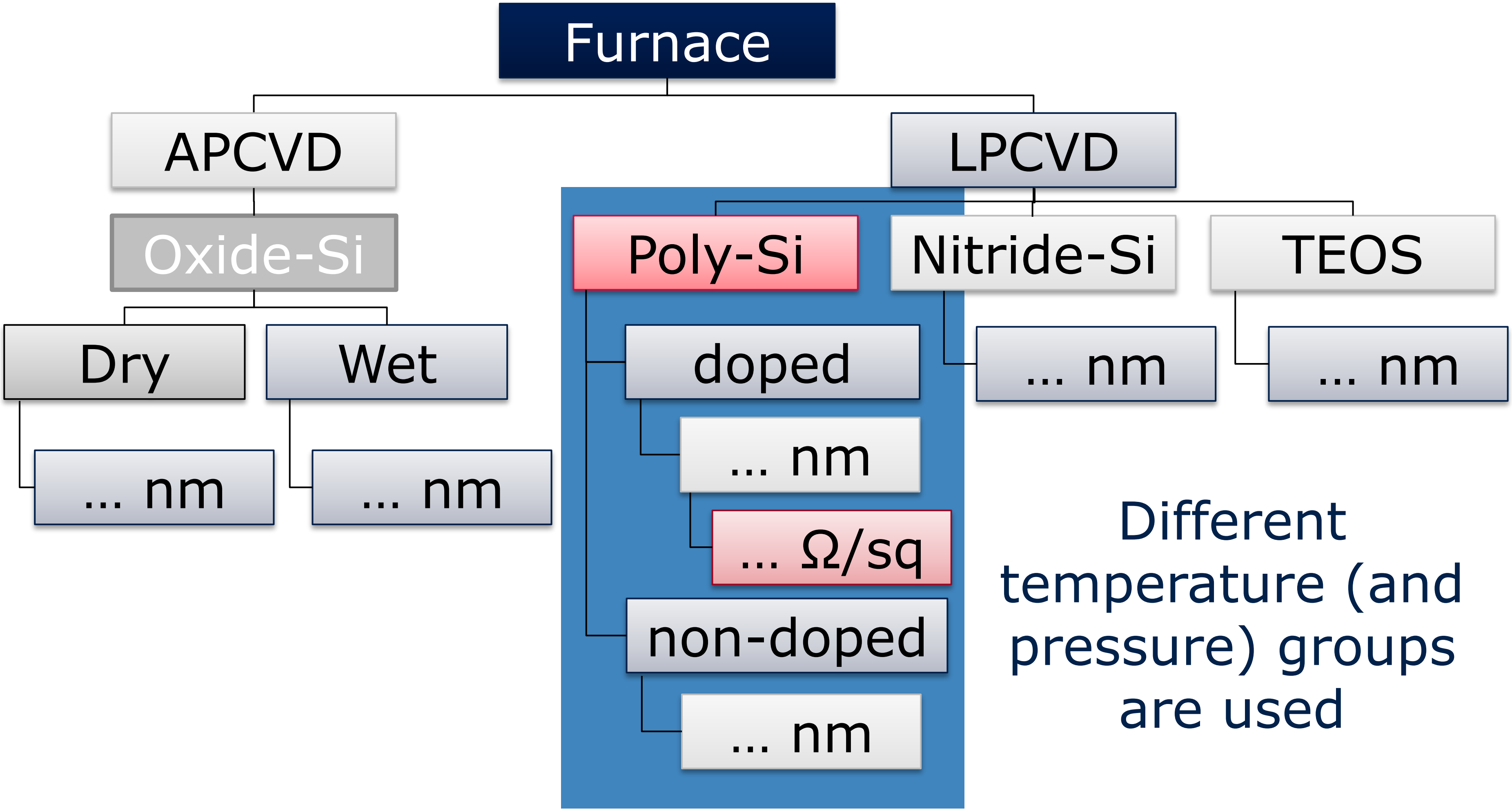
Motivation

- Reduction of the film thickness target error and the variance from batch to batch
- Improvement of the film thickness down boat uniformity
- Reduction of the sheet resistance target error and the variability from batch to batch
- Achievement of an appropriate deposition rate within given boundary conditions
- Enablement of a low sampling rate of 0.6 - 1 % with a dedicated measurement schema

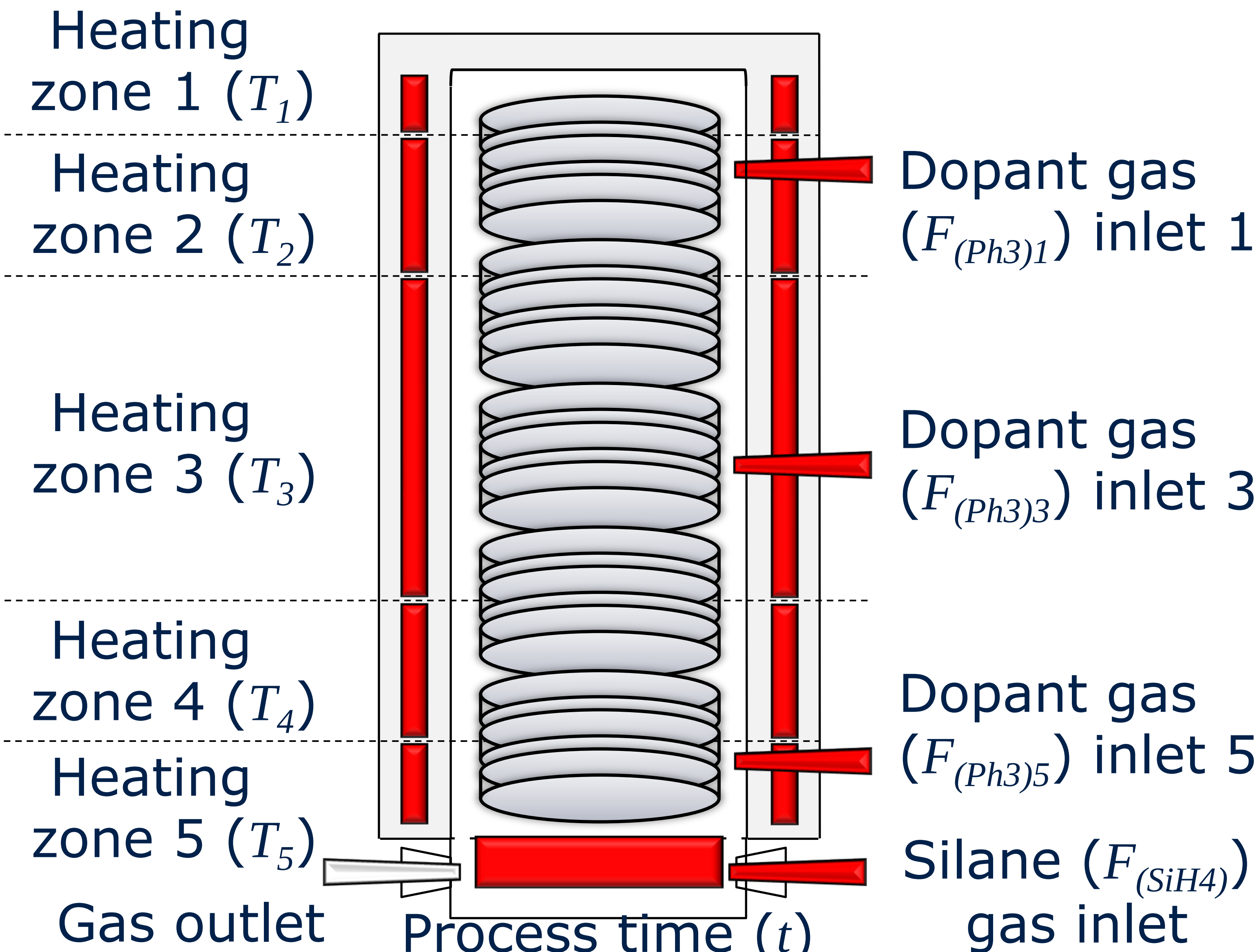
Furnace processes overview



Different temperature (and pressure) groups are used

TEOS… Tetraethylorthosilicate

Furnace tube scheme



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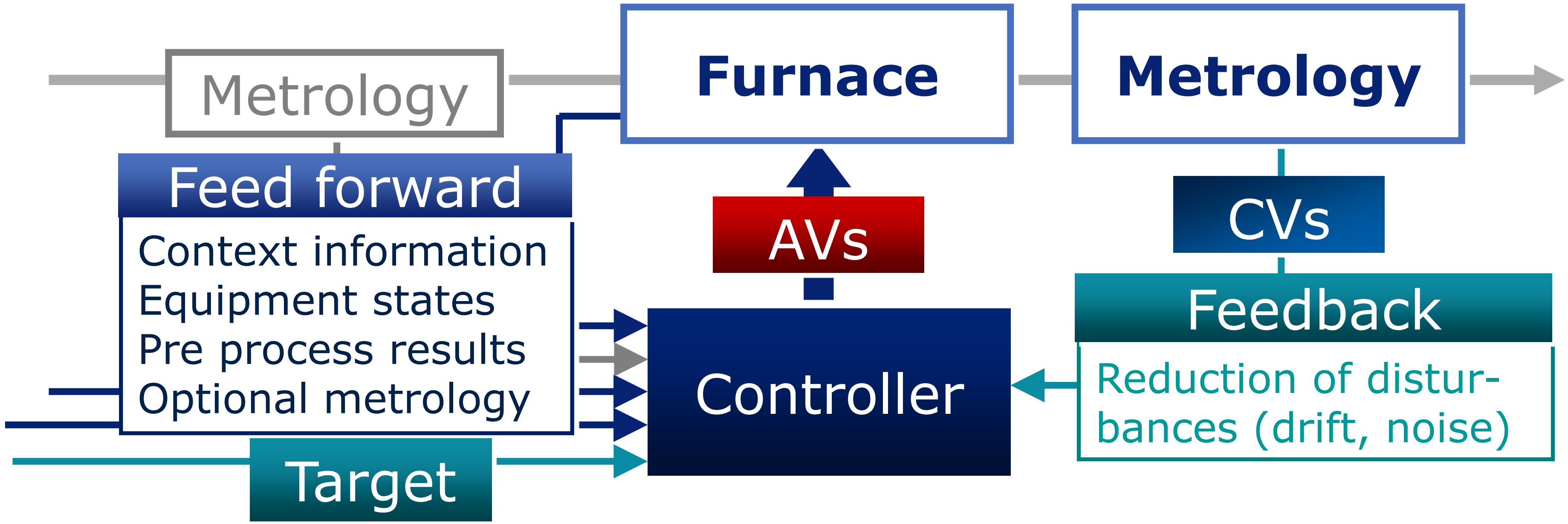
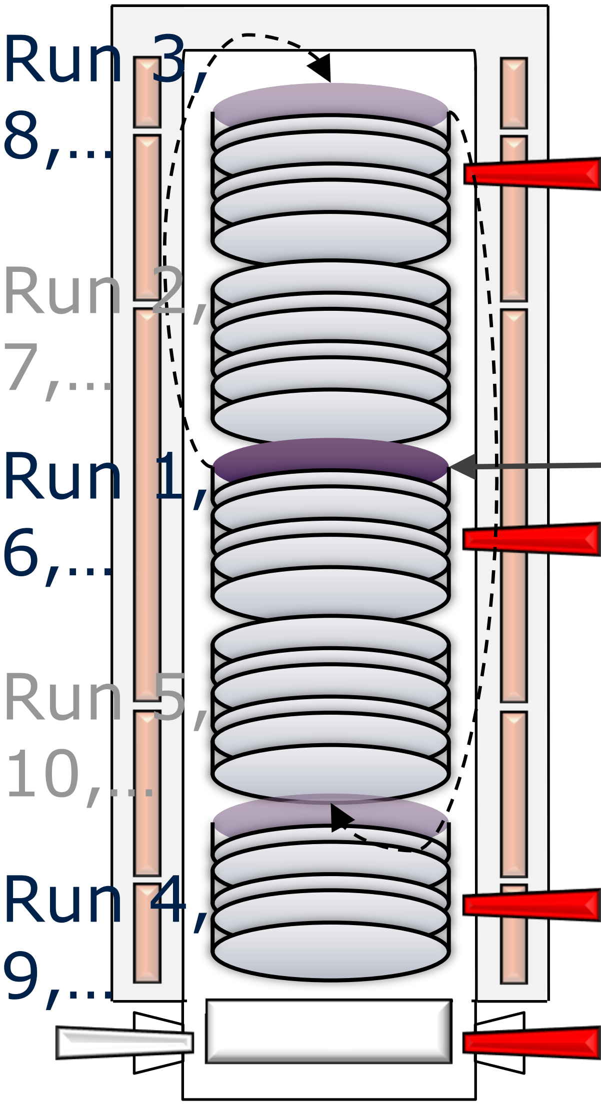
Common control flow

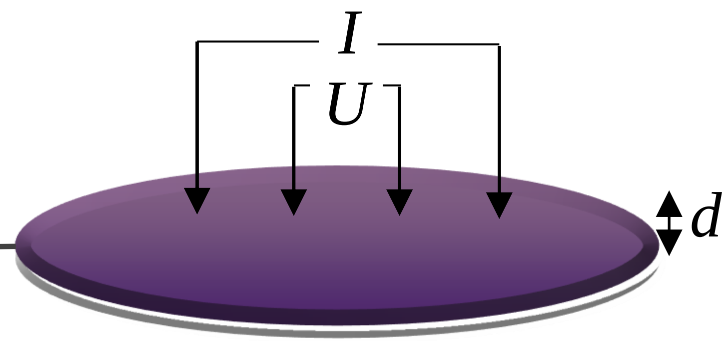


- Actuating variables (AVs) are the process time (t), the temperatures (T_i) of 5 heating zones, the silane ($F_{(SiH4)}$) and the dopant ($F_{(Ph3)i}$) gas flows of 3 inlet zones
- Control variables (CVs) are the layer thicknesses (d_i) of 5 heating zones and the layer conductivities (σ_i) (sheet resistances) of 3 gas inlet zones

Conductivity control scheme



- Measurements are cyclically performed by one **test wafer** from one gas inlet zone (1,3 or 5)



- Control variables: Conductivities (σ_i)

$$R_S = \frac{\pi}{\ln(2)} \cdot \frac{U}{I} \left[\frac{\Omega}{sq}\right] \qquad \sigma_i = \frac{1}{R_S} \cdot \frac{1}{d_i} \left[\frac{\mho}{nm}\right]$$

- Actuating variables: *Ph3* gas flows ($F_{(Ph3)i}$), *SiH4* gas flow ($F_{(SiH4)}$) [sccm]

Common conductivity model

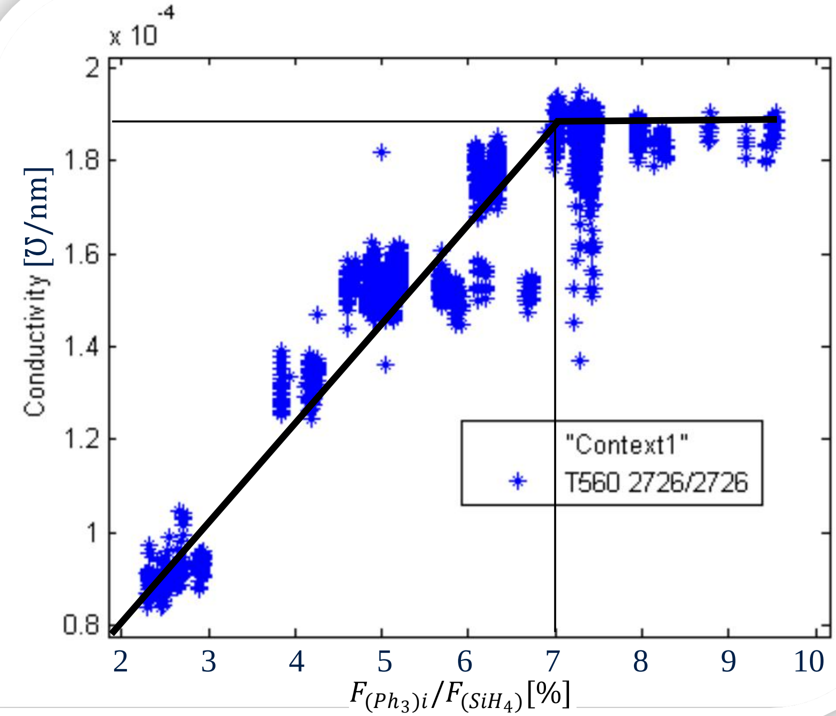
- Conductivity depends on gas flows (F_i) and nominal recipe temperature and reactor pressure

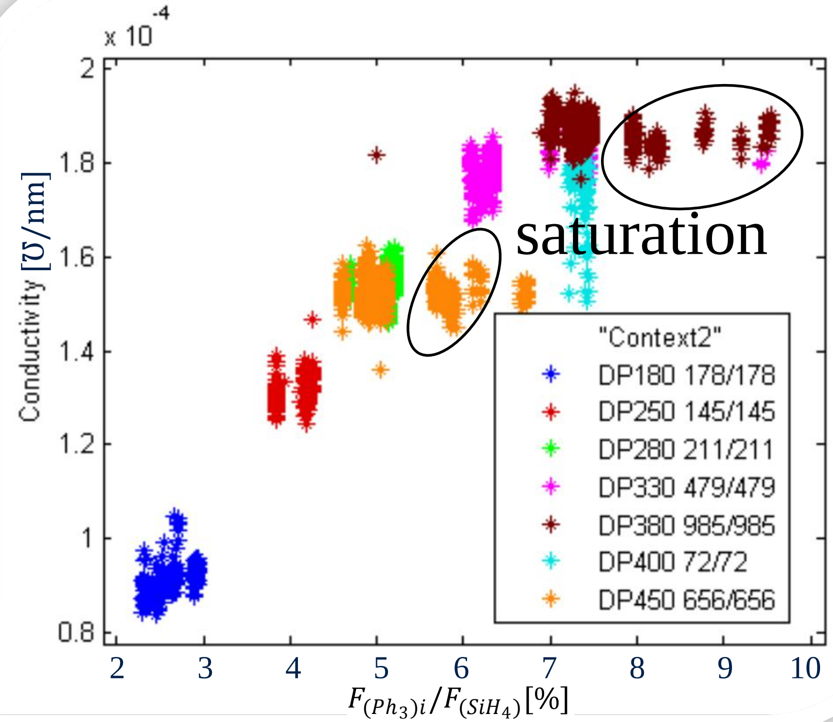
$$\begin{pmatrix} \sigma_1 \\ \sigma_3 \\ \sigma_5 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{13} & g_{15} \\ g_{31} & g_{33} & g_{35} \\ g_{51} & g_{53} & g_{55} \end{pmatrix} \cdot \begin{pmatrix} F_{(\mathrm{Ph3})_1} \\ F_{(\mathrm{Ph3})_3} \\ F_{(\mathrm{Ph3})_5} \end{pmatrix} \cdot \frac{1}{F_{(\mathrm{SiH4})}} + \begin{pmatrix} X_{C_1} \\ X_{C_3} \\ X_{C_5} \end{pmatrix}_{\mathrm{ctx}}$$

- X_{Ci} contains the zone, equipment and temperature group (context) depending state information which cover the process drifts and are updated within the controller
- No heating zone depended interactions are assumed, therefore an unitary matrix with g_σ is used

Ctx… context

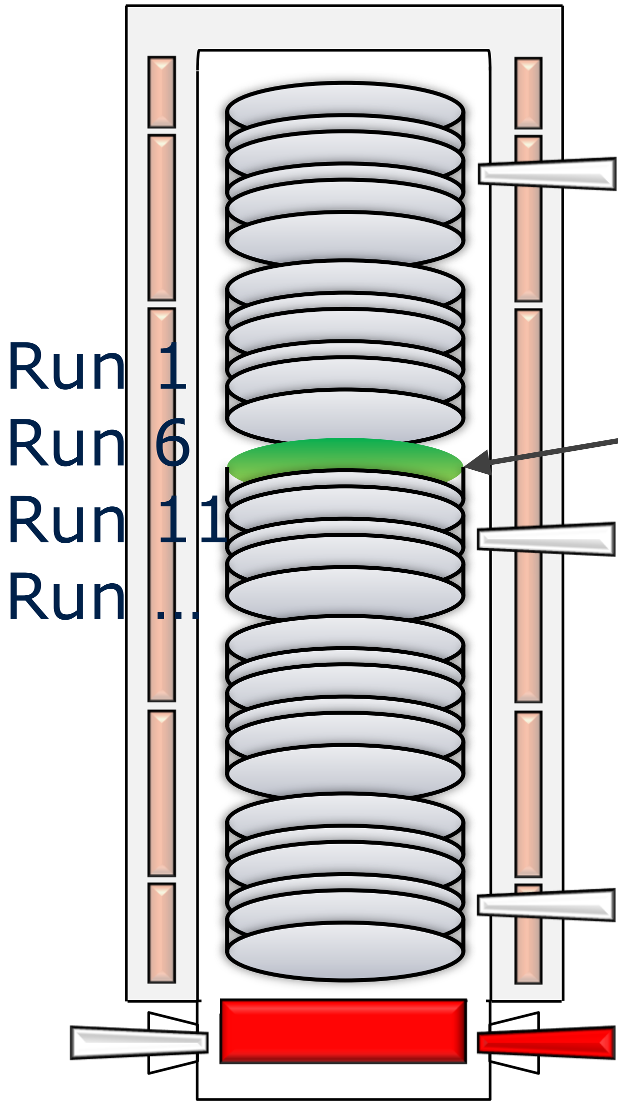
Conductivity gradient





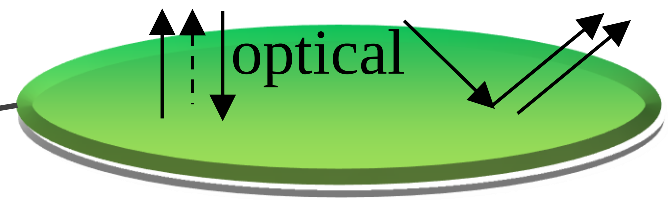
- Conductivity gradient g_σ was estimated at $2.5e^{-3}$ ℧/nm/% for relative gas flow < 7 % within context group T560
- Saturation behavior and gradient estimation depends on nominal temperature and reactor pressure

Thickness control scheme



- Zone 3 is measured by one **(test) wafer** after each 5th batch run

Interferometry or ellipsometry



- Control variables: Thickness (d), deposition rate (dr)

$$dr = \frac{d}{t}\left[\frac{nm}{min}\right]$$

- Actuating variables: Process time (t) [min], silane gas flow ($F_{(SiH4)}$) [sccm]

Common thickness model

- Center deposition rate (dr_3) depends on gas flows (F) and nominal recipe temperature and reactor pressure

$$dr_3 = g_{F_{(\mathrm{SiH4})}} \cdot F_{(\mathrm{SiH4})} - g_{F_{(rel)_3}} \cdot \frac{F_{(\mathrm{Ph3})_3}}{F_{(\mathrm{SiH4})}} + X_{R_{\mathrm{ctx}}}$$

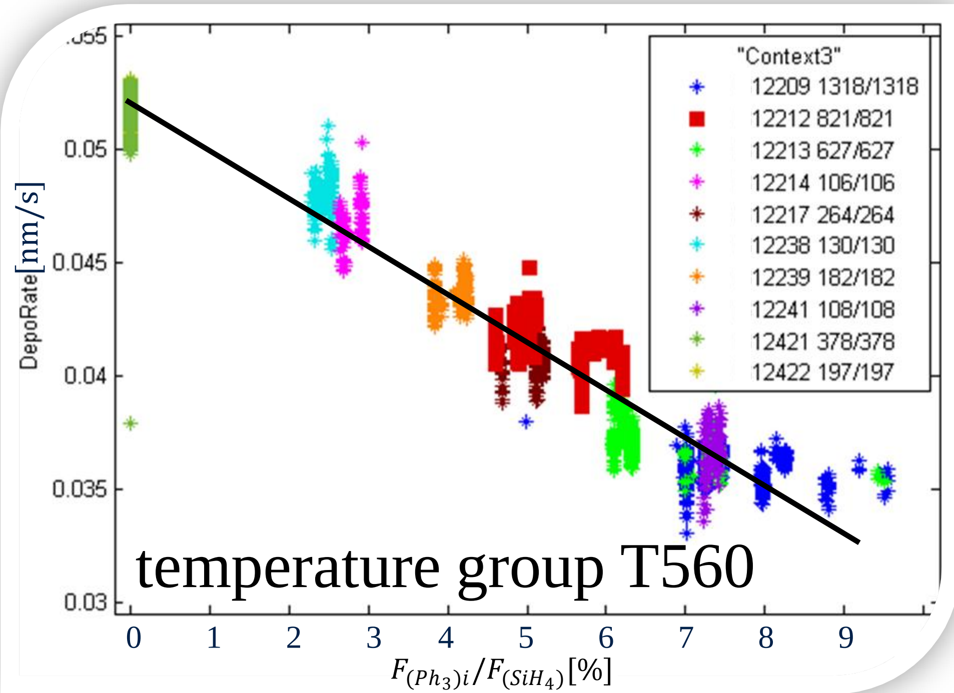
$$d_3 = dr_3 \cdot t$$

- X_R contains the zone, equipment and temperature group depending state information which cover the process drifts and are updated within the controller

$$F_{(rel)_i} = \frac{F_{(\mathrm{Ph3})_i}}{F_{(\mathrm{SiH4})}}$$

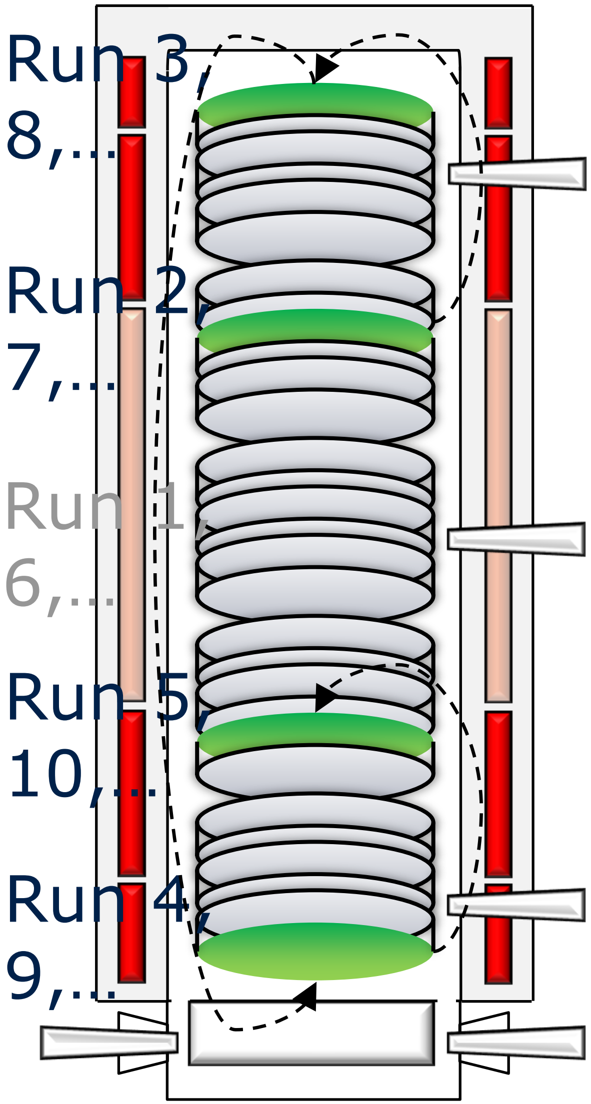
Thickness gradient

- Gradient $g_{F_{(rel)3}}$



- Deposition rate depends on dopant and silane gas flow relation. Deposition inhibitor gradient $g_{F_{(rel)3}}$ was estimated as -0.12 nm/min/%

d uniformity control scheme



- Zone 1,2,4 and 5 are cyclically measured by one **(test) wafer** run (interferometry or ellipsometry)
- Control variables: Δd_i thickness differences (i = 1,2,4,5) to zone 3

$$\Delta d_i = d_i - d_3 \, [nm]$$

- Actuating variables: Temperature offsets of zone 1,2,4,5 (T_1,T_2,T_4,T_5) to zone 3

$$\Delta T_i = T_i - T_3 \, [K]$$

d uniformity control model

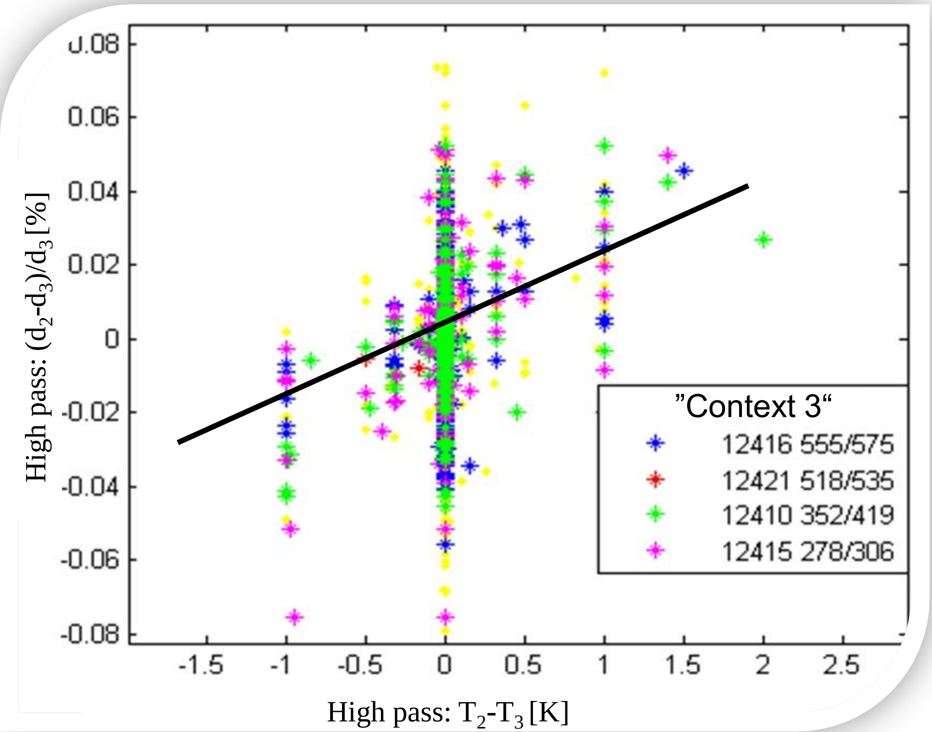
- Thickness uniformity depends on deposition rate (dr)

$$\frac{1}{d_3} \cdot \begin{pmatrix} \Delta d_1 \\ \Delta d_2 \\ \Delta d_4 \\ \Delta d_5 \end{pmatrix} = \frac{1}{dr_3} \cdot \begin{pmatrix} \frac{\delta dr_1}{\delta T_1} & \cdots & \frac{\delta dr_1}{\delta T_5} \\ \vdots & \ddots & \vdots \\ \frac{\delta dr_5}{\delta T_1} & \cdots & \frac{\delta dr_5}{\delta T_5} \end{pmatrix} \cdot \begin{pmatrix} \Delta T_1 \\ \Delta T_2 \\ \Delta T_4 \\ \Delta T_5 \end{pmatrix} + \begin{pmatrix} X_{U_1} \\ X_{U_2} \\ X_{U_4} \\ X_{U_5} \end{pmatrix}_{\text{ctx}}$$

- X_{Ui} contains the zone, equipment and temperature group depending state information which cover the process drifts and are updated within the controller
- No heating zone depended interactions are assumed, therefore an unitary matrix with g_{drT} is used

d uniformity gradient

- Gradient g_{drT}



- Temperature adjustments have an impact on relative deposition rate and thickness of 2 %/K (control gain g_{drT})

$$g_{drT} = \frac{1}{dr_3} \cdot \frac{\delta dr_2}{\delta T_2}$$

Control actions overview

1. Conductivity model (zone i =1,3,5)

$$\sigma_i = \frac{1}{R_S} \cdot \frac{1}{d_i} = g_\sigma \cdot \frac{F_{(\mathrm{Ph3})_i}}{F_{(\mathrm{SiH4})}} + X_{C_{i_{\mathrm{ctx}}}} + e_{\sigma_i}$$

2. Deposition rate model (zone i =3)

$$dr_3 = g_{F_{(\mathrm{SiH4})}} \cdot F_{(\mathrm{SiH4})} - g_{F_{(rel)}} \cdot \frac{F_{(\mathrm{Ph3})_3}}{F_{(\mathrm{SiH4})}} + X_{R_{\mathrm{ctx}}}$$

3. Thickness model (zone 3 nominal temperature)

$$d_3 = dr_3 \cdot t + e_{d_3}$$

4. Thickness uniformity model (zone i =1,2,4,5)

$$\frac{d_i - d_3}{d_3} = g_{drT} \cdot (T_i - T_3) + X_{U_{i_{\mathrm{ctx}}}} + e_{d_i}$$

- Updates of the state variables are done after performed measurements by using an EWMA filter

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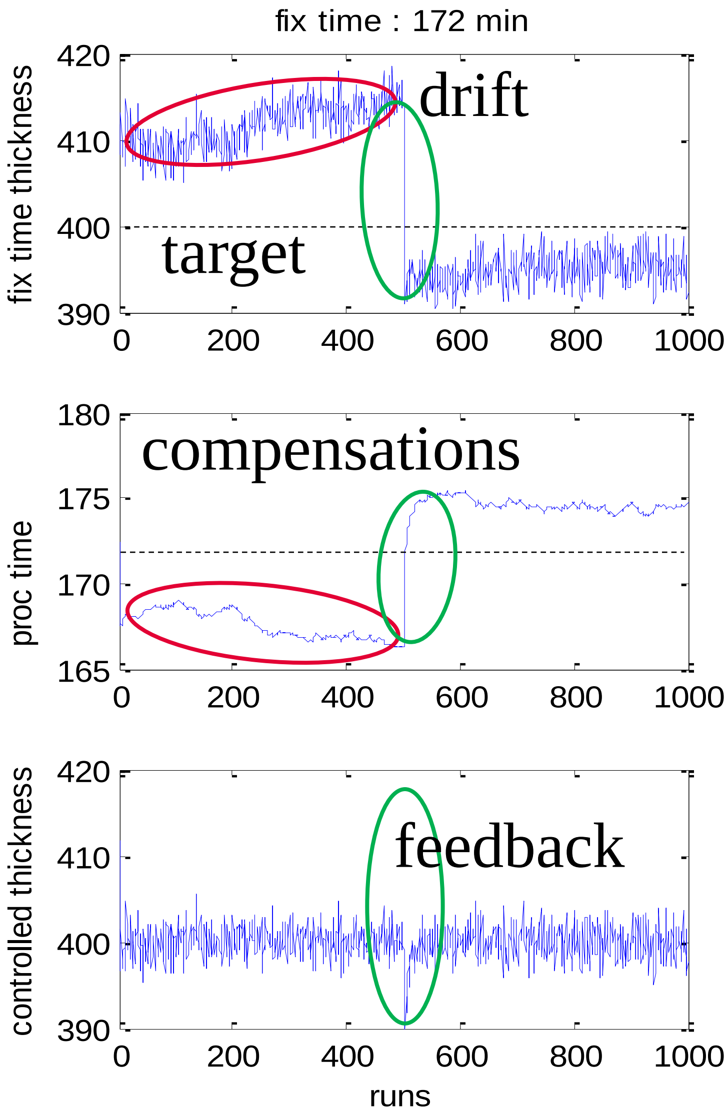
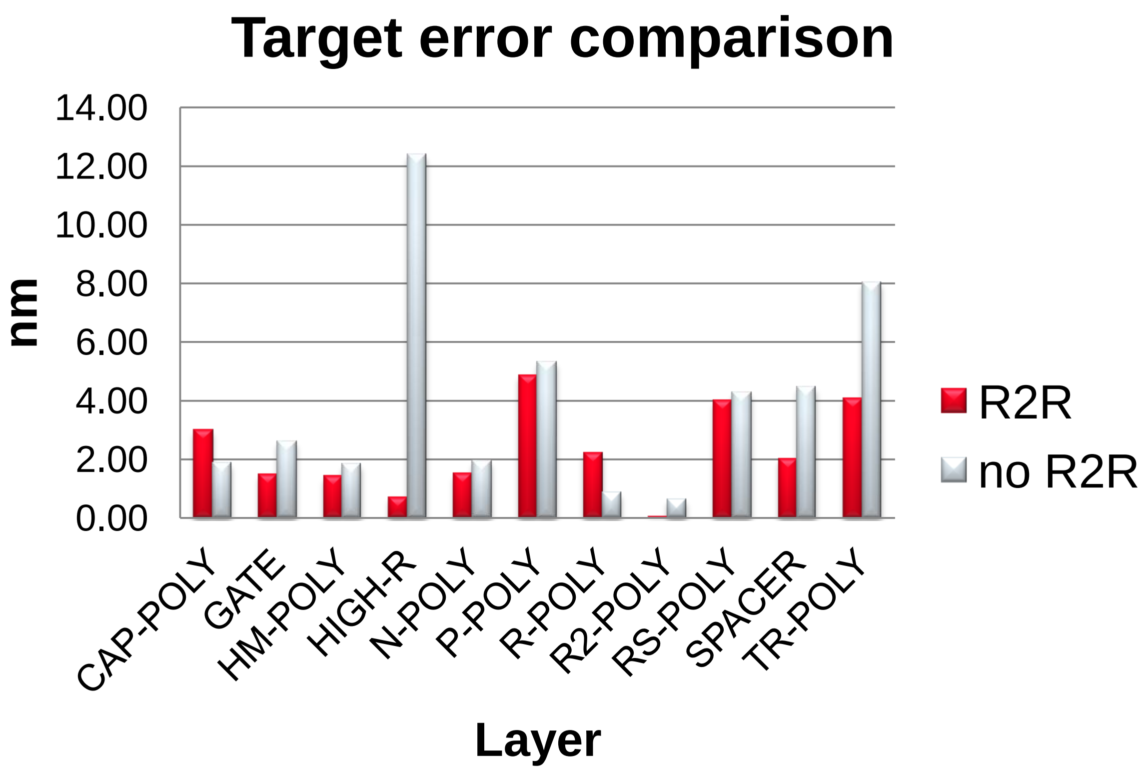
Simulation results



- Uncontrolled thickness of a fix time process with disturbances and a change of dopant gas relation from 6 % to 7 %
- Calculated process time considering relative gas flow impact on deposition rate
- Controlled thickness using recommended process time; controller removes process drifts but does not amplify noise

Productive results

- Thickness and uniformity controllers performed an improvement of target error reduction of ~ 16 % (ø) by using a metrology sampling rate of 0.6 – 1 %



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Summary

- Considering a given dedicated cyclic measurement scheme, a novel furnace control approach was introduced
- The proposed equations allow a consecutive decoupled recommendation of dopant and silane gas flows, process time and zone temperatures considering targets for conductivity, deposition rate, thickness and down boat uniformity (thickness)
- The required model parameters have been estimated from high volume production data and appropriate designed experiments (DOEs)
- Automated thickness and uniformity control have been successfully tested at production

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