Modelling and Analytical Stability Analysis of Feedback Controlled Reactive Sputter Processes

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Introduction

- Why feedback controllers are used for reactive sputtering:

  - Deposition Rate
  - Stoichiometry
  - Process stability – Short term
    Long term

3 fold increase in rate for SiO$_2$
How do we predict stability?

Approaches to evaluating stability

• Rule of thumb / best practice
• Simulation
• Analytic methods?

• Does not rely on simulation
  • Faster, more efficient
  • Deeper insight
  • Does not need interpretation – can be automated!

Modelling of the stability of reactive sputtering processes, Bartzch, Frach, Surface Coatings Technology, 2001
• A model of reactive sputtering – what kind of model?

• Low order required

• **Berg model** is ideal
Berg reactive sputter model

Three states

- $\theta_t$: Target compound coverage
- $\theta_s$: Substrate compound coverage
- $p$: Reactive gas partial pressure

$$\dot{\theta}_t(t) = \frac{1}{\rho A_t} \left( p(t) \frac{\overline{F} \alpha_t A_t}{V_c} (1 - \theta_t(t)) - \frac{J}{e} Y_c A_t \theta_t(t) \right)$$

$$\dot{\theta}_s(t) = \frac{1}{\rho A_s} \left( p(t) \frac{\overline{F} \alpha_s A_s}{V_c} (1 - \theta_t(t)) + \frac{J}{e} Y_c A_t \theta_t(t) - \frac{J}{e} Y_m A_t \theta_s(t) (1 - \theta_t(t)) \right)$$

Dynamic behaviour of the reactive sputtering process, Kubart et al, thin solid films, 2006
The MFC model is given by the equation:

$$\ddot{q}_a(t) = -2\omega_a v_a \dot{q}_a(t) + \omega_a^2 (u_c(t) - q_a(t))$$
Gas delivery

- Transport of gas from the MFC to the magnetron surface

\[ \dot{q}_p = \frac{1}{\tau_p} \left( q_a - q_p \right) \]
• Target voltage feedback

• Filtering is present in the power supply and controller

\[ \dot{V} = \frac{1}{\tau_s} (\theta_t - V) \]
$$u_c(t) = K2z(t) - K1w(t)$$

$$\dot{z}(t) = w_s - w$$

PDF control algorithm

Controller
Stability analysis method

- Equilibrium point: $\theta_{t_0}, \theta_{s_0}, p_0$
- Target state (compound coverage)
- Substrate state
- Reactive gas pressure

Calculate Eigen values

Function

Operating point
A single number that represents stability of the whole system!
A simple representation of stability

Stability analysis method
Experimental validation

- Dual rotatable cathodes – 4kW
- Al targets, O2 reactive gas
- Target voltage sensors
- Speedflo PDF controller
Experimental validation

Closed loop with default controller parameters
Experimental validation

Closed loop with default controller parameters

![Closed loop stability - Eigen values vs Experiment](image)

- **Time (s)**
- **Sensor and MFC %**
- **Experimental target voltage**
- **Setpoint**
Closed loop with K1 increased to 3

Experimental validation
Experimental validation

Closed loop with K1 increased to 3

Graph showing closed loop stability - Eigen values vs Experiment.
Case study

Software interface – automate analysis
Case study

Stability on a retro-fit reactive sputter tool

- AlOx reactive sputter deposition tool
- Planar cathodes 610mm x 130mm
- DC pulsed power, 5kW
Case study

Stability on a retro-fit reactive sputter tool

- Customer was unable to stabilise the process at the desired setpoint
- Automated and manual tuning was ineffective

80% compound coverage ratio
Case study

Stability on a retro-fit reactive sputter tool

• Model predicts unstable process control with default tuning parameters
• Is there a combination of tuning parameters that will stabilize the process?
Case study

Stability on a retro-fit reactive sputter tool

Add a 3rd dimension!

• No combination of tuning parameters results in a stable solution

• Cant solve this problem by tuning the controller
Case study

Stability on a retro-fit reactive sputter tool

3x increase in pumping speed

- Stable solution is now possible
- Installing 2 more pumps is not very practical!
Case study

Stability on a retro-fit reactive sputter tool

Reduction in gas distribution pipe from 2m to 50cm

- Large range of stable controller parameters
Case study

Stability on a retro-fit reactive sputter tool

- Gas pipe distribution modified so that MFC is on the chamber wall
- The process is now stabilizable at the required setpoint

Controller auto-tuning
Case study

Stability on a retro-fit reactive sputter tool

- Gas pipe distribution modified so that MFC is on the chamber wall
- The process is now stabilizable at the required setpoint

![Graph showing process stability](image)
Summary

• A simple tool for investigating and predicting the stability of a reactive sputter process

• Can be used at the system design stage or for troubleshooting problems

• Does not replace experimental (or automated) tuning of the controller

Future possibilities:

• Latest models

• Co-sputtering, dual reactive gases

• Multiple process zones and gas injection points – stability of interactions

• Software environment

Conclusions
Thank you for your attention!

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