Modelling and Analytical Stability Analysis of Feedback Controlled Reactive Sputter Processes

Joe Brindley, Benoit Daniel, Victor Bellido-Gonzalez, Dermot Monaghan

Gencoa Ltd, UK

1st May 2019
Why feedback controllers are used for reactive sputtering:

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

3 fold increase in rate for SiO₂
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

\( \dot{\theta}_t(t) = \frac{1}{\rho A_t} \left( p(t) \overline{Fr} \alpha_t A_t (1 - \theta_t(t)) - \frac{J_e Y_c A_t}{e} \theta_t(t) \right) \)

\( \theta_s \) Substrate compound coverage

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

\( p \) Reactive gas partial pressure

Dynamic behaviour of the reactive sputtering process, Kubart et al, thin solid films, 2006
\[
\ddot{q}_a(t) = -2\omega_a v_a \dot{q}_a(t) + \omega_a^2 (u_c(t) - q_a(t))
\]
Gas delivery

- Transport of gas from the MFC to the magnetron surface

\[ \dot{q}_p = \frac{1}{\tau_p} (q_a - q_p) \]
• 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
Stability analysis method

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

Function

Calculate Eigen values

Operating point
A single number that represents stability of the whole system!
Stability analysis method

A simple representation of stability

- **Stable region**
- **Unstable region**
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

![Graph showing closed loop stability - Eigen values vs Experiment](image)
Experimental validation

Closed loop with K1 increased to 3
Experimental validation

Closed loop with $K_1$ increased to 3

![Graph showing closed loop stability - Eigen values vs Experiment](image-url)
Case study

Software interface – automate analysis
Case study

Stability on a retro-fit reactive sputter tool

- AIOx 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 3^{rd} 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
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

Process stable
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*

*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

---

*Journal of Physics D: Applied Physics*

*A time-dependent model for reactive sputter deposition*

K Strijckmans and D Depla

Published 8 May 2014
Thank you for your attention!

Please visit us at Booth 720