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Tuning Rule for Linear Control of Nonlinear Reactive Sputter Processes

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***Abstract*—A tuning rule for the linear control of nonlinear reactive sputter processes is developed based on a process model, which has the form of an Abel differential equation. The process characteristics relates to a supercritical Pitchfork bifurcation with stable and unstable equilibrium states. The paper presents a tuning rule to achieve a desired closed-loop transition behavior and set-point following for step-shaped reference signals without the need of an identified process model. The tuning rule is deduced from the given stability conditions. Experiments are presented for the validation of the developed control structure and the proposed tuning rule. They show that reactive sputter processes can be systematically tuned to achieve a desired closed-loop behavior.**

***Keywords*—nonlinear systems, tuning rule, PID control, reactive sputter process**

I. INTRODUCTION

Reactive sputter processes are low-pressure plasma-driven processes for thin film deposition on substrates. The fabrication of optical reflective layers, superconductive layers, hard coatings and integrated circuits are applications of reactive sputter processes. Low-pressure plasmas are operated at a pressure of a few pascals and a degree of ionisation of 10^{-5} [1]. These process conditions make coatings of anorganic and organic materials possible, but the plasma-surface interaction may cause the instability of certain operating points.

The unstable operating points result from a nonlinear interaction between the solid surfaces and a reactive gas. The main process principle requires a background gas as argon to be ionized by an electrical field between two electrodes. Ions are accelerated towards the surfaces and remove surface atoms by a collision cascade in the solid. The sputtered atoms are moved from an electrically driven target (sputtered electrode) towards a grounded or biased substrate (electrode, to be covered) to build up a thin nanostructured layer. In addition, a gas reacts with the thin layer and changes the surface conditions, which can cause a positive feedback from the reactive gas pressure towards the thin film surface conditions.

In this paper, a new control method for nonlinear reactive sputter processes is presented based on a process model, which has the form of an Abel differential equation.

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II. LITERATURE SURVEY

The control of reactive sputter processes is mainly discussed in the fields of vacuum science and thin solid films. In these scientific fields the monitoring of process variables and the realization of an experimental set-up is investigated. Examples are the process supervision by electrical [2] or optical control variables [3], [4]. Although the stabilization of reactive sputter processes is required to enable, for example, 50 to 100 % higher thin film deposition rates [5], these studies do not deliver control design methods or relationships between specific feedback control laws and parameters.

Feedback control-oriented approaches in literature are based on the linearization of a physically motivated model, which is known as the Berg model [6]. Hence, a proportional-derivate (PD) controller [7] and a linear-quadratic (LQ) regulator [8] are developed with reactive gas flow as manipulated variable and reactive gas pressure as controlled variable. However, the validation of the developed controllers is done by static measurements or static simulation studies and no trajectories have been shown. Furthermore, no tuning rules are proposed.

Reactive sputter processes are typically described by the Berg model [6] with analysis of its static behavior [9], extensions regarding further physical effects [10], further dynamics [11] and asymmetric effects [12]. The process instability is described by the Berg model with an “unstable hysteresis region” [13]. Fig. 1 shows the simulated static input/output behavior of the system with the “unstable hysteresis region” and the metallic and poisoned process modes.

In this paper, the closed-loop tuning of nonlinear reactive sputter processes shall be investigated based on a reduced model. For this purpose, a new control method with a linear control law is developed based on Lyapunov’s direct method. Intervals for the controller parameters with respect to the

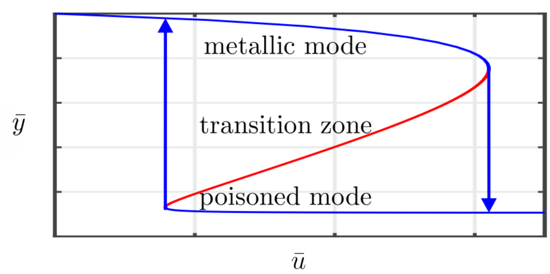

Fig. 1. Simulation of the static input/output behavior of the system with the Berg model. The blue arrows indicate that the “unstable hysteresis region” is not visible in open loop, because the relating steady states are unstable.

process parameters to achieve a stable control loop are presented and allow the formulation of a tuning rule. Hence, a tuning rule is proposed. For the validation of the tuning algorithm experiments are presented. The experiments address the questions of the applicability of the tuning rule to the plant, the influence of different initial conditions and the required controller structure for a stationarily exact control loop.

III. PROCESS MODEL

The three modes (metallic, transition, poisoned) of reactive sputter processes are represented by the Berg model with a nonlinear ODE of third order and at least fifteen parameters like sticking coefficients or sputter yields. The three state variables, represented in Fig. 2 are the partial pressure $p_O(t)$, the normalized coverage of the target $\theta_T(t)$ and the normalized coverage of the substrate $\theta_S(t)$.

The main process principle requires that an argon ion flux J_{Ar} sputters new metal or oxidized metal particles from the target and a gas reacts with the unreacted surface areas $(1-\theta_i(t))$. The target sputtering leads to a metal flow $F_{Me}(t)$ and a metal oxide flow $F_{MeOx}(t)$ from the target to the substrate. The flows $F_{Me}(t)$ and $F_{MeOx}(t)$ influence the relation between the unreacted substrate surface $(1-\theta_S(t))$ and the reacted substrate surface $\theta_S(t)$. The input of reactive gas $Q_{In}(t)$ increases $p_O(t)$ and the pumped outflow $Q_{Out}(t)$ decreases $p_O(t)$. The partial pressure $p_O(t)$ converts unreacted metal to reacted metal and, therefore, can shift the relation between the unreacted surfaces (blue coloured) and reacted surfaces (brown coloured). These conversion rates regarding the target and substrate area are described by $Q_T(t)$ and $Q_S(t)$.

If the substrate area is high oxidized, because a thin film with a corresponding stoichiometry shall be deposited, a positive feedback in the system occurs. A nearly fully oxidized substrate leads to a more and more oxidized target, because the substrate becomes less and less a sink with the target as the only remaining sink for reactive gas. Due to a lower sputter yield (quotient of sputtered atoms to incoming argon ions) of the oxidized surface compared to the unoxidized surfaces, a more and more oxidized target has a lower sputter rate than an unoxidized target. A lower sputter rate leads to less new metal atoms at the substrate and, therefore, to a higher substrate coverage with metal oxide. The reactive gas partial pressure increases because less reactive gas can react with the vanishing unreacted surface areas, which in turn accelerates the target oxidation. Hence, this positive feedback has to be stabilized by feedback control to achieve a constant deposition rate and thin film stoichiometry.

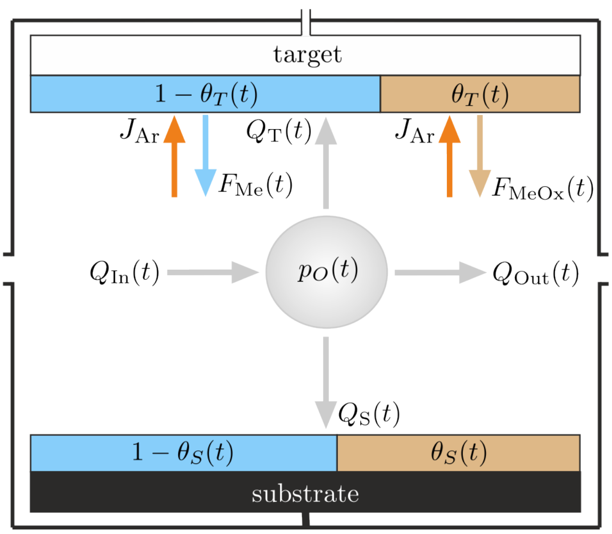

Fig. 2. Sketch of a plasma reactor for reactive sputter deposition.

On a macroscopic level these processes can be summarized by an Abel differential equation with one state variable and five parameters. The model reduction and parameter identification are described in [14]. The reduced model focuses on the approximation of the stability properties and the input/output behavior of the Berg model. The Abel differential equation is

$$\dot{y}(t) = Ay^3(t) + By^2(t) + Cy(t) + D + Eu(t) \tag{1}$$

with $y(t) \in [0,1]$, real parameters A, B, C, D, E and $(C - \frac{B^2}{3A}) > 0$. The first restriction considers the system saturation and the last restriction considers the three ambiguous input/output characteristic.

The closed-loop system with a PIDT$_1$-controller is shown in Fig. 3. A DT$_1$-element (derivative lag element) is used instead of a pure D-element for a realizable controller. The PIDT$_1$-controller

$$\begin{aligned} u(t) &= u_i(t) + u_d(t) + k_p e(t), \\ u_d(t) &= -x_d(t) + k_d e(t), \\ \dot{u}_i(t) &= k_i e(t), \\ \dot{x}_d(t) &= -k_t x_d(t) + k_d k_t e(t) \end{aligned} \tag{2}$$

leads to the first state equation of the closed-loop model

$$\begin{aligned} \dot{y}_c(t) = &A{y_c}^3(t) + B{y_c}^2(t) \\ &+ C_{pid} y_c(t) + D_{pid}(t) + b(u_i(t) - x_d(t)) \end{aligned}$$

with

$$b = E, \quad C_{pid} = C - b(k_p + k_d), \quad D_{pid}(t) = D + b(k_p + k_d)w(t)$$

and the summarized state-space model of the closed loop

$$\begin{aligned} \dot{x}_1(t) &= p(x_1(t)) + D_{pid}(t) + bx_2(t) - bx_3(t), \\ \dot{x}_2(t) &= k_i w(t) - k_i x_1(t), \\ \dot{x}_3(t) &= k_d k_t w(t) - k_d k_t x_1(t) - k_t x_3(t) \end{aligned} \tag{3}$$

with

$$\begin{aligned} x_1(t) = y_c(t), \quad x_2(t) = u_i(t), \quad x_3(t) = x_d(t), \\ p(x_1(t)) = A{x_1}^3(t) + B{x_1}^2(t) + C_{pid} x_1(t). \end{aligned}$$

IV. LINEAR CONTROL

In this section a rule for the tuning of a linear controller to stabilize nonlinear reactive sputter processes is presented. Based on the given process model (3) it will be shown that intervals for the control parameters of a stable feedback loop can be specified. Hence, a tuning procedure can be proposed.

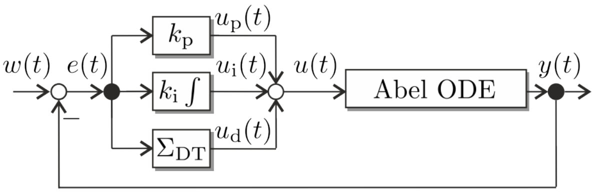

Fig. 3. Closed loop with $PIDT_1$-controller and reduced model (Abel ordinary differential equation) as plant

A. Transformation of the state space representation

In order to investigate the stability of the dynamic model (3) with Lyapunov's direct method [15], a transformation concerning the equilibrium states of the system is needed and a constant reference input $\bar{w} = w(t)$ is considered.

A linear controller can manipulate the closed-loop model by C_{pid} such that only one equilibrium state remains. For this, the function $\bar{p}(\bar{x}_1) = A\bar{x}_1^3 + B\bar{x}_1^2 + C_{\text{pid}}\bar{x}_1$ needs to be strictly monotonously decreasing or increasing. The function $\bar{p}(\bar{x}_1)$ has no local extreme points if and only if the discriminant $\Delta_{\bar{p}'} = 4B^2 - 12AC_{\text{pid}}$ of $\frac{\delta \bar{p}(\bar{x}_1)}{\delta \bar{x}_1} = 3A\bar{x}_1^2 + 2B\bar{x}_1 + C_{\text{pid}}$ is negative or zero, because in this case there does not exist any real solution for the quadratic equation and for $A < 0$ the antiderivative is strictly monotonously decreasing. Hence, it is assumed that $k_p + k_d$ is chosen such that the function $p(x_1(t))$ is strictly monotonously decreasing with

$$k_p + k_d \le \frac{1}{E}\left(C - \frac{B^2}{3A}\right) \quad \text{for} \quad E < 0,$$

$$k_p + k_d \ge \frac{1}{E}\left(C - \frac{B^2}{3A}\right) \quad \text{for} \quad E > 0.$$

The only remaining equilibrium state can be shifted to the origin with respect to the second state equation by

$$x_1(t) = \tilde{x}_1(t) + \bar{w} \;\Rightarrow\; \dot{x}_2(t) = -k_i\tilde{x}_1(t) \tag{4}$$

with

$$\begin{aligned}\dot{\tilde{x}}_1(t) &= p(\tilde{x}_1(t) + \bar{w}) + \bar{D}_{\text{pid}} + bx_2(t) - bx_3(t)\\ &= \tilde{p}(\tilde{x}_1(t)) + k_1 + bx_2(t) - bx_3(t),\\ \dot{x}_3(t) &= -k_t x_3(t) - k_d k_t \tilde{x}_1(t)\end{aligned}$$

and

$$\begin{aligned}\tilde{p}(\tilde{x}_1(t)) &= A\tilde{x}_1^3(t) + \tilde{B}\tilde{x}_1^2(t) + \tilde{C}_{\text{pid}}\tilde{x}_1(t),\\ \tilde{B} = B + 3A\bar{w},\; \tilde{C}_{\text{pid}} &= 3A\bar{w}^2 + 2B\bar{w} + C_{\text{pid}},\\ k_1 &= A\bar{w}^3 + B\bar{w}^2 + C_{\text{pid}}\bar{w} + \bar{D}_{\text{pid}}.\end{aligned}$$

It can be moved to origin with respect to the first state equation by

$$x_2(t) = \tilde{x}_2(t) - \frac{k_1}{b} \;\Rightarrow\; \dot{\tilde{x}}_1(t) = \tilde{p}(\tilde{x}_1(t)) + b\tilde{x}_2(t) - bx_3(t). \tag{5}$$

The transformed state-space model can be expressed as

$$\begin{aligned}\dot{\tilde{x}}_1(t) &= \tilde{p}(\tilde{x}_1(t)) + b\tilde{x}_2(t) - bx_3(t),\\ \dot{\tilde{x}}_2(t) &= -k_i\tilde{x}_1(t),\\ \dot{x}_3(t) &= -k_t x_3(t) - k_d k_t \tilde{x}_1(t).\end{aligned} \tag{6}$$

B. Lyapunov based stability analysis

Lyapunov's direct method is now applied to the model (6) with the following candidate Lyapunov function:

$$V(\tilde{x}_1(t),\tilde{x}_2(t),x_3(t)) = \frac{1}{2}V_1\tilde{x}_1^2(t) + \frac{1}{2}V_2\tilde{x}_2^2(t) + \frac{1}{2}V_3x_3^2(t).$$
$$V_1 > 0,\; V_2 > 0,\; V_3 > 0.$$

The derivate of V is

$$\begin{aligned}&\dot{V}(\tilde{x}_1(t),\tilde{x}_2(t),x_3(t))\\ &= \tilde{p}(\tilde{x}_1(t))\tilde{x}_1(t)V_1 + \tilde{x}_1(t)\tilde{x}_2(t)(bV_1 - k_iV_2)\\ &\quad -k_tV_3x_3^2(t) + \tilde{x}_1(t)x_3(t)(-bV_1 - k_tk_dV_3).\end{aligned} \tag{7}$$

The first term has to be negative for any $\tilde{x}_1(t)$, which leads to a condition regarding k_p:

$$\begin{aligned}k_p &\le \frac{1}{E}\left(C - \frac{B^2}{3A}\right) - k_d, \quad \text{for} \quad E < 0,\\ k_p &\ge \frac{1}{E}\left(C - \frac{B^2}{3A}\right) - k_d, \quad \text{for} \quad E > 0.\end{aligned} \tag{8}$$

The second term of $\dot{V}(\tilde{x}_1(t),\tilde{x}_2(t),x_3(t))$ vanishes, if the feedback is negative heading to a condition regarding k_i:

$$k_iE > 0. \tag{9}$$

The third term of $\dot{V}(\tilde{x}_1(t),\tilde{x}_2(t),x_3(t))$ is only negative, if the time-constant k_t is positive and therefore the internal feedback in the DT_1-element has to be negative:

$$k_t > 0. \tag{10}$$

The fourth term of $\dot{V}(\tilde{x}_1(t),\tilde{x}_2(t),x_3(t))$ vanishes analogously to (9), if the feedback is negative:

$$k_dE > 0. \tag{11}$$

A $PIDT_1$-controller with control parameters satisfying the given conditions (8)-(11) leads to a set-point following control loop because of $\tilde{x}_1(t \to \infty) = 0$ and $x_1(t \to \infty) = y(t \to \infty) = \bar{w}$ with (4). A PI-controller also leads to a stationarily exact control loop, because (4) is not influenced of the DT_1-element and the state space transformation to the origin (5) still holds for $x_3(t) = 0$. The additional degrees of freedom of the DT_1-element can be used to achieve further performance demands.

A pure P-controller or a PDT_1-controller do not guarantee a stationarily exact control loop for any combination of $\bar{w}$ and the control parameters. For example the closed-loop state space representation of (1) with a P-controller is

$$\dot{x}_1(t) = Ax_1^3(t) + Bx_1^2(t) + (C - bk_p)x_1 + (D + bk_p\bar{w})$$

with $x_1(t) = \tilde{x}_1(t) + \bar{w}$ is

$$\begin{aligned}\dot{\tilde{x}}_1(t) = &A\tilde{x}_1^3(t) + \tilde{B}\tilde{x}_1^2(t) + (3A\bar{w}^2 + 2B\bar{w} + C - bk_p)\tilde{x}_1(t)\\ &+ A\bar{w}^3 + B\bar{w}^2 + C\bar{w} + D\end{aligned}$$

which is only zero for $\tilde{x}_1 = 0$ with $A\bar{w}^3 + B\bar{w}^2 + C\bar{w} = -D$. Hence, a transformation $x_1(t) = \tilde{x}_1(t) + \alpha(D + bk_p\bar{w})$ or the specific value $k_p = -\frac{D}{b\bar{w}}$ is needed to shift the equilibrium state to the origin for a specific $\bar{w}$. Hence, set-point tracking is only achieved for a specific pair $(\bar{w}, k_p)$. An additional DT_1-element does not change the qualitative structure of (3) with respect to the required transformation of the first state variable and set-point following cannot be guaranteed, either. These results are in line with the Internal Model Principle.

Stability theorem:
Reactive sputter processes of the form of an Abel differential equation (1) can be stabilized for constant reference signals by a linear static controller, which manipulates the closed-loop model such that the function $p(x_1(t))$ is strictly monotonously decreasing. If the linear controller includes an integrator or derivative lag element the resulting feedback has to be negative.

Set-point following theorem:
In line with the Internal Model Principle reactive sputter processes, which have the form of an Abel differential equation (1), are set-point tracking for constant reference signals, if the open loop contains an integrator element and the closed loop is stabilized.

Interpretation:
The parameter D of the model (1) does not influence the state stability of the system with respect to the unstable equilibrium states and can be neglected for the control design. Condition (10) is independent of the system parameters, because k_t has always to be positive. The conditions (9) and (11) represent structural properties with respect to the direction of action of the input. The sign of E of the model (1) can be determined by a consideration of the process physics or by experiments. Hence, intervals for the control parameters of a stable closed-loop system can be summarized:

$$\begin{aligned} &k_\mathrm{p} \in [k_{\mathrm{p,crit}} = \frac{1}{E}\left(C - \frac{B^2}{3A}\right) - k_\mathrm{d}, \mathrm{sgn}(E)\ \infty), \\ &k_\mathrm{i} \in (0, \mathrm{sgn}(E)\ \infty), \\ &k_\mathrm{t} \in \mathbb{R}_+^*, \\ &k_\mathrm{d} \in (0, \mathrm{sgn}(E)\ \infty). \end{aligned}$$

The proposed parameter intervals allow the formulation of a tuning procedure. Simulation studies to investigate the transition behavior indicate that the conditions (8), (9) and (10) are necessary and sufficient for the stability of the closed-loop system. The condition (11) seems only be sufficient. A higher $|k_\mathrm{p}|$ with respect to the sign of E seems to damp the oscillation of the controlled variable. A higher $|k_\mathrm{i}|$ and $|k_\mathrm{d}|$ with respect to the sign of E seem to accelerate the rising time of the closed loop but can lead to overshooting.

C. Tuning procedure

A tuning procedure can be deduced from the results (7) - (11) and simulation studies. The knowledge of the sign of the parameter E is sufficient for the application of the following tuning algorithm.

The resulting tuning procedure can be related to the tuning of a PID-controller with respect to a linear plant. In contrast to the tuning of a linear plant the output signal of the nonlinear plant will oscillate between the saturated process modes for unsuitable controller parameters. In addition, it can not be expected that an once tuned linear controller will ensure a desired dynamic closed-loop behavior for any set-point change.

It is therefore essential to validate the proposed tuning procedure by experiments for the considered reactive sputter process. The experiments shall also address the influence of different initial conditions and controller structures to the closed-loop behavior.

Preconditions:
The process can be temporally operated with oscillations between the metallic and poisoned mode and the influence of the input is known by the sign of E.

Initial values for the controller parameters:

As starting point small absolute values for k_p and k_i might be chosen with respect to the sign of E:

a) If $E < 0$ the controller parameters k_p and k_i have to be necessarily negative.
b) If $E > 0$ the controller parameters k_p and k_i have to be necessarily positive.

The signs of k_p and k_i shall not be changed in the following tuning procedure. The start value for k_d shall be zero. The expected transition time t_t of the closed loop shall determine the parameter $k_\mathrm{t} = \frac{3}{t_\mathrm{t}}$.

Make experiments with the closed-loop system with the current controller parameters for tuning of k_p, k_i and k_d:

1. Tuning of k_p:
   If the process oscillates for an adjusted k_p, the absolute value of k_p has to be increased till the system oscillation is damped with acceptable input values or otherwise decreased.
2. Tuning of k_i:
   If the process is overshooting for an adjusted k_i, the absolute value of k_i has to be reduced or otherwise increased to accelerate the rising time of the closed loop with acceptable input values.
3. If the system behavior is non-oscillating with acceptable overshooting, k_d shall be tuned or otherwise the last two steps shall be repeated.
4. Tuning of k_d:
   If the process behavior has a slow transition time for an adjusted k_d, the absolute value of k_d has to be increased till a acceptable dynamic behavior with respect to the input is achieved.
5. If the process behavior is not acceptable the first and second step shall be repeated otherwise the algorithm shall be terminated.

Result:
Stable control loop with desired dynamic behavior.

V. EXPERIMENTS

A. Experimental set-up

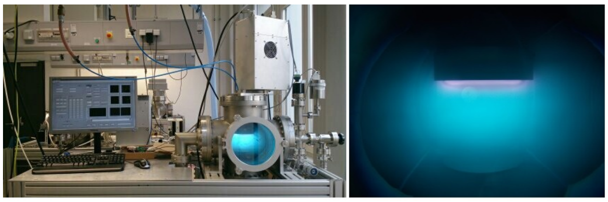

Fig. 4. Experimental set-up with process control computer and reactor chamber (left) and plasma discharge (right)

The validation of the presented control design method is proceeded in a stainless steal magnetically enhanced low-pressure plasma reactor (Fig. 4). The background gas is argon with a pressure of 3 pascals and the reactive gas is molecular oxygen. A generator power of 350 watts is used to sputter an aluminum target. As actuator for the input of reactive gas, measured in standard cubic centimeter per minute, a MKS mass flow controller is used. The output variable, the normalized bias voltage at the driven electrode, is measured by a AE CESAR 136 RF power generator. The presented controller is implemented on a process PC with LabVIEW as control software and 50 milli seconds as sampling time. All measurements are proceeded in a thermally stable initial state.

B. Validation of the tuning procedure

The experiments used in the tuning procedure to achieve a stable control loop are shown in Figs. 5 and 6. As starting point the following control parameters with respect to a negative sign of E are chosen:

$$k_{\mathrm{p}} = -0.5 \quad k_{\mathrm{i}} = -0.1 \quad k_{\mathrm{t}} = 0.05 \quad k_{\mathrm{d}} = 0.$$

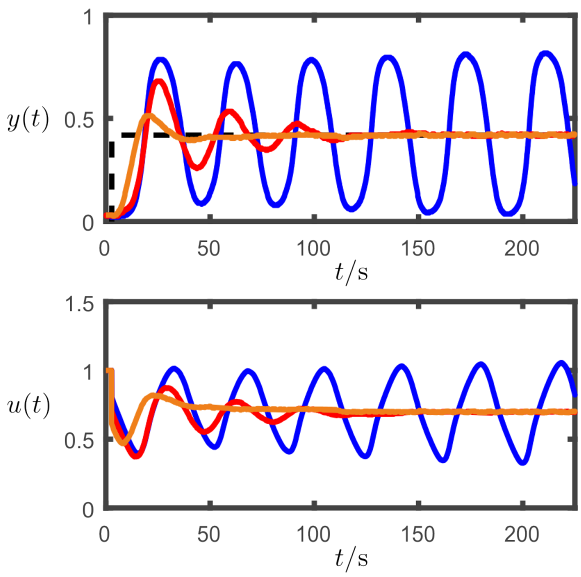

Fig. 5. Measured control variable $y(t)$ and input signal $u(t)$ in closed loop with a PI-controller ($k_{\mathrm{i}} = -0.1$; $k_{\mathrm{p}} = -0.5$ (blue), $k_{\mathrm{p}} = -0.75$ (red), $k_{\mathrm{p}} = -1$ (orange)). The black dashed line shows the set point $w(t)$.

In the first step of the tuning algorithm k_{p} shall be tuned till the system oscillation is damped, which is shown in Fig. 5. The parameter k_{p} has been varied from -0.5 (semi-stable) over -0.75 (damped oscillating) to -1 (damped with insignificant oscillating). In the experiments a permanent oscillation of $y(t)$ can be still observed for $k_{\mathrm{p}} = -0.7$. Hence, the critical proportional gain $k_{\mathrm{p,crit}}$ can be localized in the range of $k_{\mathrm{p}} \in [-0.75, -0.70)$.

In the second step of the tuning procedure k_{i} shall be tuned till the system overshooting is negligible. Fig. 6 demonstrates that k_{i} has to be decreased from -0.1 to -0.035 to reduce the overshooting.

As the system behavior is non-oscillating with acceptable overshooting for $k_{\mathrm{p}} = -1$ and $k_{\mathrm{i}} = -0.035$, k_{d} has to be tuned.

In the fourth step of the tuning procedure k_{d} has been determined to $k_{\mathrm{d}} = -0.75$ to reduce the transition time of the closed loop (Fig. 6).

In order to further decrease the transition time of the closed loop the second step of the tuning procedure has to be repeated. Hence, k_{i} has been tuned to $k_{\mathrm{i}} = -0.07$ to achieve a closed loop with a fast transition time with no overshooting (Fig. 6). The input values are in the range of 0.3 to 1, which is acceptable.

Fig. 6 also shows that the chosen control parameters

$$k_{\mathrm{p}} = -1 \quad k_{\mathrm{i}} = -0.07 \quad k_{\mathrm{t}} = 0.05 \quad k_{\mathrm{d}} = -0.75$$

are sufficient to achieve a stationarily exact control loop even if the initial state is located in the metallic process mode. However, in this case a noticeable overshooting occurs, which can be related to the nonlinear process behavior. Hence, a specific set point change requires a specific controller tuning if performance demands shall be considered. If only a stable closed loop without a specific dynamic behavior is acceptable,

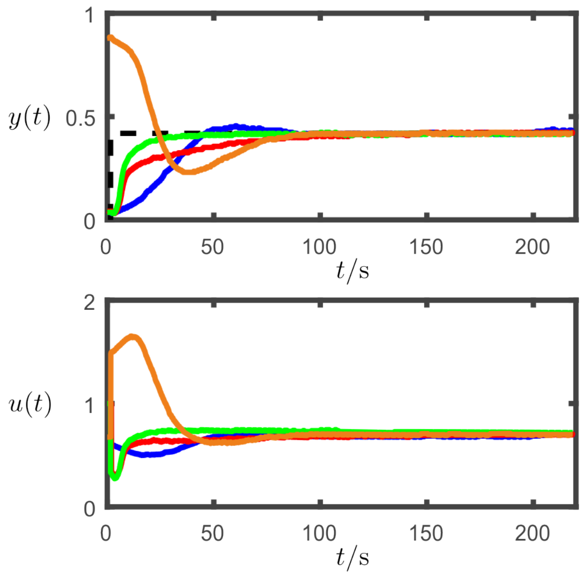

Fig. 6. Measured control variable $y(t)$ and input signal $u(t)$ in closed loop with a $\mathrm{PIDT_1}$-controller ($k_{\mathrm{p}} = -1$; $k_{\mathrm{i}} = -0.035$ and $k_{\mathrm{d}} = 0$ (blue), $k_{\mathrm{i}} = -0.035$ and $k_{\mathrm{d}} = -0.75$ with $k_{\mathrm{t}} = 0.05$ (red), $k_{\mathrm{i}} = -0.07$ and $k_{\mathrm{d}} = -0.75$ with $k_{\mathrm{t}} = 0.05$ (green, orange). The start value of the green and orange colored trajectories are located in the poisoned and metallic mode. The black dashed line shows the set point $w(t)$.

a single tuning procedure with respect to the desired operating point is sufficient.

The rise of the input $u(t)$ in Fig. 6 can be explained by a comparison with Fig. 1. If the start value is located in the metallic mode the input has to exceed a critical value to enable a trajectory into the transition zone. After entering the transition zone the input value has to be reduced to last in the transition zone. If the initial value is located in the poisoned mode the opposite behavior of the input occurs.

Experiments without an integrator element in the controller are shown in Fig. 7. Only for specific set point changes a pure P- or PDT_1-controller is sufficient to achieve an almost set-point tracking control loop. Hence, only a PI- oder $PIDT_1$-controller guarantees a stationarily exact control loop with respect to $k_{p,crit}$ for any set point change.

VI. CONCLUSION

A new approach to the control of reactive sputter processes with the reactive gas flow as manipulated variable and the normalized bias voltage as measured variable has been presented. The experiments demonstrate that the application of the proposed tuning rule leads to a stable closed loop with a desired dynamic behavior.

These results raise the question as a robust control approach with a calculation of the controller parameters based on an estimated process model is useful, which shall be investigated in a future paper. In this context, also an in-depth analysis concerning the accessability of the process by its linearized model shall be done.

Building on this, MIMO-models with plasma or thin film values as measured variables and appropriate control designs shall be researched.

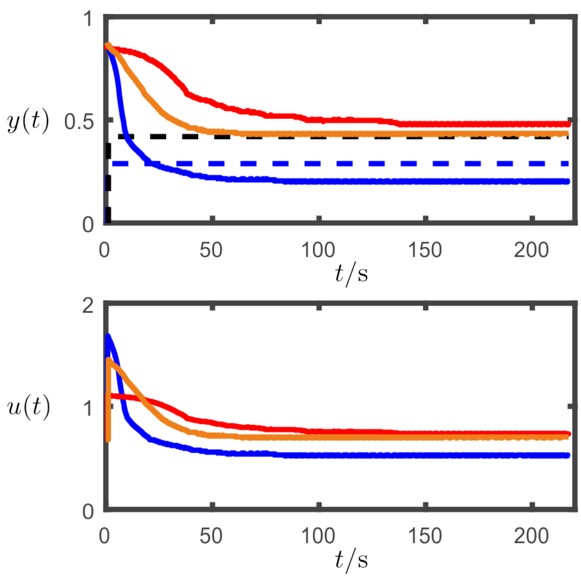

Fig. 7. Measured control variable $y(t)$ and input signal $u(t)$ in closed loop with a PDT_1-controller ($k_p = -1$; $k_d = -0.75$ with $k_t = 0.05$ (blue, orange), $k_d = 0$ (red)). The red and orange colored trajectories are related to the black dashed set point and the blue colored trajectory is related to the blue dashed set point. The initial conditions of all trajectories are equal and located in the metallic process mode.

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REFERENCES

[1] M. Lieberman and A. Lichtenberg, *Principles of Plasma Discharges and Material Processing*, John Wiley & Sons, Inc, USA, 2005.

[2] J. Kazuss, V. Kozlov and E. Machevski, Control of reactive deposition process by stabilization of the power supply work, *Society of Vacuum Coaters, 54th Annual Technical Conference Proceedings*, 2011, pp. 419-422.

[3] V. Bellido-Gonzalez, B. Daniel, J. Counsell and D. Monaghan, Flexible gas control for reactive magnetron sputtering process, *Proceedings of AIMCAL*, Charleston, USA, 2004, pp. 1-8.

[4] R. A. Swady, Process control of reactive mangetron sputtering of thin films of zirconium dioxides, *International Journal of Nanoelectronics and Materials*, 2011, 4, pp. 59-63.

[5] V. Bellido-Gonzalez, B. Daniel, D. Monaghan and J. Counsell, Uniformity control in reactive magnetron sputtering, *Glass Performance Days China*, 2009.

[6] S. Berg, H. O. Blom, T. Larsson and C. Nender, Modeling of reactive sputtering of compound materials, *Journal of Vacuum Science and Technology A*, 1987, 5, pp. 202-207.

[7] M. A. George, E. A. Craves, R. Shehab and K. Knox, Analysis of closed loop control and sensor for a reactive sputtering drum coater, *Journal of Vacuum Science and Technology A*, 2004, 22, pp. 1804-1809.

[8] D. J. Christie, Making magnetron sputtering work: Modelling reactive sputtering dynamics, part 2, *Society of Vacuum Coaters Bulletin, Spring*, 2015, pp. 30-33.

[9] S. Berg and T. Nyberg, Fundamental understanding and modeling of reactive sputtering processes, *Thin Solid Films*, 2005, 476, pp. 215-230.

[10] S. Berg, E. Saerhammar and T. Nyberg, Upgrading the Berg-model for reactive sputtering processes, *Thin Solid Films*, 2014, 565, pp. 186-192.

[11] T. Kubart, O. Kappertz, T. Nyberg and S. Berg, Dynamic behaviour of the reactive sputtering process, *Thin Solid Films*, 2006, 515, pp. 421-424.

[12] K. Strijckmans and D. Depla, A time-dependent model for reactive sputter deposition, *Journal of Physics D: Applied Physics*, 2014, 47, pp. 1-13.

[13] S. Berg, H. O. Blom, M. Moradi, C. Nender and T. Larsson, Process modeling of reactive sputtering, *Journal of Vacuum Science and Technology A*, 1989, 7, pp.1225-1229.

[14] C. Woelfel, P. Awakowicz and J. Lunze, Model reduction and identification of nonlinear reactive sputter processes, To appear in *IFAC 2017 World Congress*, 2017.

[15] H. Khalil, *Nonlinear Systems*, Pearson Education Limited, Great Britain, 2014.