Uniformity Control in Reactive Magnetron Sputtering

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Abstract
Magnetron sputtering is an industrial coating deposition technique which is commonly used in glass coating industry in order to add functionality and properties to the base glass. The deposition of the coating substantially differs from the composition of the magnetron sputtering targets (e.g. TiOx coatings deposited from Ti targets) or coating physicochemical properties differ much of the sputtered or co-sputtered target (e.g. high power ZnS). Up to a certain point magnetron sputtering has been a tolerated necessity. Glass Coating Industry has ‘opted-out’ on certain reactive sputtering processes in order to gain process stability and reproducibility.

Introduction
Any control process relies on 3 key elements [1]:
• sensors, with adequate sensing ability of the correct system signal
• actuators, with adequate ability to implement changes to the system
• process controller, able to gather sensing information, processing and communicating the adequate response to the actuators.

Correct flow of information linking the 3 elements of the control system is very important.

A perfect control would require to find the correct sensors, process controller, actuators, and the adequacy of signal information flow across those three elements. Any faults in that network would limit the ability to control the process.

One of the important areas in the upscalability of glass processes is the ability to improve productivity while maintaining or improving product quality. For some of the vacuum (or non vacuum) coating technologies involved in glass processing, uniformity over large area is a limiting factor in contention with coating deposition rate. In particular for Reactive Magnetron Sputtering processes this has brought different solutions.

Magnetron Sputtering is a Physical Vapour Deposition technique, in which the source of material comes from an element called “target” (either in solid or even liquid form). Material from the target is converted into a “vapour” flux through a phenomenon called sputtering. Sputtering is a high energy ion bombardment process able to remove or lift off material from the target onto the vacuum creating a material vapour flux. In magnetron sputtering the ions needed for the bombardment of the target are generated on a plasma created on the vicinity of the target surface. The plasma is trapped by a combination of electric and magnetic field confinement, based on a magnetron principle.

Reactive magnetron sputtering occurs whenever the deposited chemical composition of the coating substantially differs from the composition of the magnetron sputtering targets (e.g. TiOx coatings deposited from Ti targets) or coating physicochemical properties differ much of the sputtered or co-sputtered target (e.g. high power ZnS). Up to a certain point magnetron sputtering has been a tolerated necessity. Glass Coating Industry has ‘opted-out’ on certain reactive sputtering processes in order to gain process stability and reproducibility. The use of compound targets has already been adopted, e.g. ITO, ZnO:Al; and more recently TiOx which has the potential of replacing Ti reactive sputtering. Most of these compound targets still would require a certain degree of reactive sputtering, especially for large area deposition requiring high coating uniformity. However, the general idea in those instances has been to limit the required control level to a minimum, almost entirely based on control of inputs rather than the monitoring of outputs. One of the key elements in maintaining a uniform reactive sputtering process over a large area under control, is the sensor or sensors which are used as reference in the closed loop control. The lack of stable sensors, and / or misuse or misplacement of sensors, has led the industry in many instances to take safer options. The present paper would try to highlight the current sensor availability with its pros and cons in large area uniform reactive magnetron sputtering deposition.

Figure 1
The reactive sputtering control offers the possibility of higher rate deposition than a fully poisoned condition (Setpoint = 100% in the above graph)

![Graph showing Si and SiOx rates at 23 kW (dual rotatable) with Setpoint (O2 emission 777nm)]
thermodynamically stable compound. And that would also apply when using a compound target. When it comes to reactive magnetron sputtering processes the same would apply. A general misconception is that the reactive sputtering control will render a unique composition on the substrate as long as there is enough reactive gas available for the formation of a stoichiometric composition. The reality is that there are many other factors.

The main focus of the present paper is the need for adequate sensors in order to achieve control. In the particular case of the control of coating uniformity this is also true. It is not uncommon to see that the industrial solution, when it comes to reactive magnetron sputtering, is to operate the process on an open loop (that is with no feedback control). There are many reasons behind that decision, but the main one is that this is the fail safe option. However, there are costs associated with using this fail safe option. One of these costs is on product throughput. Typically coating rates could be enhanced by 50 to 100% when using feedback control. Another of these costs is the energy associated with the deposition process.

Control

In reactive magnetron sputtering there are 3 main types of sensors which industry uses:
- Optical – plasma emission monitoring
- Partial pressure of reactive gas species
- Impedance – e.g. target voltage feedback

In all sensor choices the important elements are that the sensor is sensing the correct variable and that the sensor has a long term stability. The first 2 groups of sensors offer the possibility of uniformity control across a large area as the signal and the actuations could be localised to the area which needs a uniformity trim. The impedance sensors would generally give an overall cathode status, and would need to be used in combination with PEM or Partial Pressure sensors in order to control uniformity over a large area. In certain situations if the system is very stable a single impedance signal could be used as long as adequate slave local actuations could be arranged. The present paper will focus mainly on the uniformity control via PEM and partial Pressure sensors.

Plasma Emission Monitoring (PEM)

Typically light is collected from a plasma source. One of the main problems associated with these plasma sources is that they are also coating sources. When the coating covers the monitoring window, the intensity of light collected decreases. Therefore the design of the light collector and the positioning on the system are key for long term stability. Figure 2 shows an example of one of the plasma emission light collectors manufactured by Gencoa.

The plasma signal brings spectral information. The spectrum will contain information on the chemical elements of the target and gas phase. Provided that many other things remain constant, the variation on the intensity of emission gives a reliable feedback on the amount of such element presence on the vapour phase. The typical use of these sensors is when different actuation is required along the length of a large magnetron or coating unit. By sensing the plasma emission on each section, and acting upon it, the uniformity across a large area could be maintained. Figure 3 shows an example of this trimming effect in action. The control is generally split into independent or Master/Slaved control sections. Figure 3 shows results for a 3 PEM points. Different actuations on each section enable the control from +/- 2.5% to +/- 1.2% uniformity.

PEM could be a very useful sensor whenever there are complex or multiple influences in the deposition process, for example, neighbouring plasma processes and load/lock influences in an in-line coater. Figure 4 shows an arrangement (typical) of NbOx / SiOx targets for antireflective coatings. Figure 5 shows that when not having an active control on one of the units (e.g. all reactive gases on constant flow) the setpoint of the neighbour affects what is achieved on the side that is believed to be on “constant & stable” condition with no feedback control. Figure 6 shows an example with e areas uniformity control.
showing periodic variations on the need of reactive gas introduced by the actuators.

In reactive processes the reactive gas is being shared between the main reactive gas pumps, which are the sputtered metals. This is due to the reactive gas being pumped preferentially towards the plasma process.

The above figure demonstrates that even in “fail safe options” that have been taken by the industry, the failure of one of the sputtering sections would have an effect on the neighbouring areas, and that would give different product quality. The use of adequate independent control could in fact be an even safer option.

**Partial Pressure sensors**

The basis for uniformity control when using other sensors is very similar to PEM. The sensor should be able to gather “local” information on the area that needs affecting by the actuators. Local partial pressure could be measured by sensors which are specific to a particular gas, for example O₂ sensors (Lambda sensors), or via remote plasma excitation of gas species, as for example using a Penning Gauge PEM [2]. Figure 7 shows a schematic of an Oxygen Sensor (Lambda sensor) and the electrochemical principle behind the functionality of the sensor.

The remote plasma emission monitoring based on a Penning gauge plasma (Penning-PEM) has been previously reported by the authors [2]. This sensor has the advantage that could be sensing a variety of gas species (unlike the Oxygen sensor which is only suitable for O₂). An example cross referencing the Oxygen sensor signal with the Penning-PEM signal and the target voltage (for a Ti-O₂ process) is given in Figure 8. Figure 8 shows a hysteresis reactive gas ramp (of O₂) on a Ti magnetron sputtering plasma process. The voltage signal is typical for the Ti family (also seen on Nb for example) as it indicates the transition from metal mode to poisoned mode. The partial pressure of reactive gas is “seen” by a lambda sensor (inverse mode, more O₂ produces less signal) and by a Penning-PEM (direct mode, more O₂ excess produces more signal).

An example of the sensitivity of the Penning-PEM is given in Figure 9, where the Penning-PEM signal is recorded when there is Ti plasma, or when there is no Ti plasma. The hysteresis ramp produces an immediate increase in signal as the gas is injected when there is no O₂ consumption (Ti plasma is off). However, when there is a Ti plasma on the penning-PEM starts to see the excess of O₂ after some of the initially injected O₂ has been consumed by the Ti plasma.
Conclusions

Large Area Uniformity coating using reactive magnetron sputtering has been demonstrated on an industrial scale.

One of the key elements in maintaining a uniform reactive sputtering process over a large area under control is the sensor, or sensors, which are used as reference in the closed loop control.

The lack of stable sensors, and / or misuse or misplacement of sensors, has led the industry in many instances to take safer options. Some of the safer options, could be in fact unstable when it comes to a sudden failure or change on one of the plasma sections of the in-line system, for example, or when the load/lock system brings different gas flows added to the reactive mix.

PEM and Partial Pressure Sensors have been demonstrated to enable good uniformity control.

The authors recommend the use of Oxygen Sensors (Lambda) and Penning-PEM as Partial Pressure sensors which are easily implemented over a large area enabling local information and local responses in order to control the uniformity.

The advantage of Penning-PEM over Oxygen sensors (Lambda) is that the Penning-PEM is able to sense a variety of gas species, unlike the Lambda sensor which only is sensitive to partial pressure of O₂.

References
