

# Eliminating short and long term drifts in reactive sputter coating of glass

Dermot Monaghan, Victor Bellido-Gonzalez, Benoit Daniel, Sarah Powell, John Counsell  
Gencoa Ltd, Physics Rd, Liverpool, L24 9HP, UK

Keywords

1=Reactive sputtering    2=Magnetron    3=PEM    4=Process monitoring and control

## Abstract

This paper introduces the concept of combining fast and slow feedback control with measured plasma properties in order to maintain a systems operation at optimum level with enhanced up-time and reduced energy costs. Plasma emission monitoring (PEM) for fast feedback control is typically used when maintaining a reactive sputtering process in high rate transition mode. Slow feedback can be used to determine the state of the system and measure drifts in plasma properties with time and provide the appropriate corrections or operator warnings. The slow feedback is 'condition monitoring' and helps to predict maintenance cycles and failure of the plasma process. This results in products within the given specifications. In order to provide a more robust PEM response from the process an ex-situ method is illustrated that used the plasma within a typical Penning vacuum measurement gauge to provide the process information. This can be used as a stand-alone signal or in combination with in-situ PEM measurements to enhance the suite of possible 'sensors' used to decide on the direction and maintenance of the process.

## Plasma Emission Monitoring

The use of a plasma emission monitoring (PEM) based feedback control for reactive sputtering is now well established as a means to increase the rates and provide stability in the transition region on a target surface [1-4]. Another signal that can be used for effective reactive gas control is the target voltage [5]. Whilst a target voltage signal is easier to 'collect' and can be the best mode of operation in

some cases, it does not give as much information as the data given by the plasma spectrum. Generally for PEM based gas control only one or two plasma species are monitored to provide the 'sensor' in the process. However more data is available from the plasma spectrum and this gives a complete picture of the elements present in the plasma environment, see figure 1.

The different intensities displayed within the spectrum represent all the chemical species present and can be identified by the wavelength of the transmission. Consequently, background levels of species such as hydrogen, oxygen and nitrogen can also be identified. As changes occur in the process plasma, the signal intensity will vary for the specific species. Figure 2 illustrates the effects of different levels of oxygen gas input to a sputtering process and the 'poisoning' of the target that will completely suppress sputtering of titanium metal at high enough gas flows. This is represented by a decrease in the Ti signal intensity.

The sensor uses this decrease in signal intensity as a measure of the plasma environment and provides an input into a fast process controller in order to maintain the balance of metal and oxygen at the optimum level for high rate deposition and control of the film stoichiometry. This is the basis of PEM feedback control and when combined with an advanced numerical algorithm such as PDF+ [3] and a well designed gas distribution system, total stability at any point on the hysteretic curve can be achieved in what is otherwise a highly unstable process.

Due to the scale of a large area glass coating system and the tight uniformity requirements, it is necessary to have multiple monitoring points in order

to balance the gas distribution and pumping effects over 3-4m lengths, see figure 3.

## Stability of the plasma emission signal

An advantage of the PEM technique is that it is very sensitive to changes in the plasma environment. Conversely, in industrial situations this can also be its weakness. It can be influenced by any change in the plasma intensity which may not necessarily be a result of a real process demand for more or less gas. Such aspects that can change the plasma intensity are:

- Substrate interference with the vacuum pumping and magnetron plasma
- Changes in the system anode – coating with insulating material
- Coating up with time of the fibre-optic system by coating flux
- Changes in the substrate or chamber out-gassing and moisture partial pressure
- Changes in the pumping efficiency and pressure

It is therefore wise to use more than one plasma emission line in order to provide a better baseline. A common method is to measure the Argon emission and to ratio this with the metal or gas signal. By doing this, fluctuations that occur in the plasma can be normalized to some degree in the short and long term.

## Ex-situ plasma emission monitoring

In order to ensure that the inputs to the gas controller or monitoring system have an added degree of robustness, it is possible to make a plasma emission measurement of the gas environment away from the process plasma where these in process disturbances do not

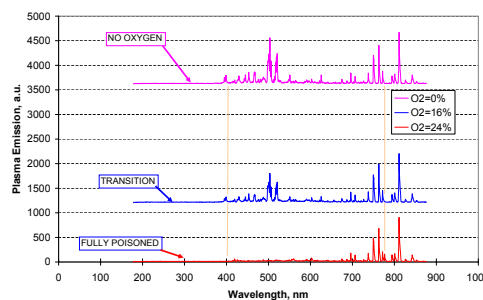
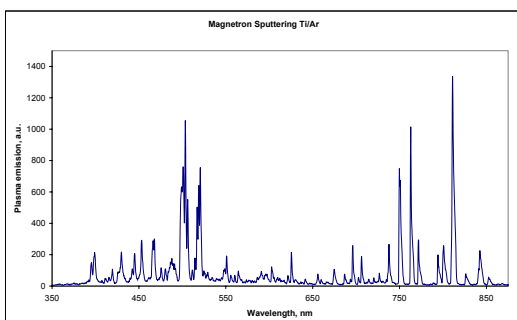


Figure 1 (far left)  
Plasma emission spectrum of titanium sputtered in the presence of argon

Figure 2  
Plasma emission spectrum of titanium sputtered in the presence of argon and oxygen with increasing amounts of oxygen

occur. In order to do this a remote plasma generation device is required that is representative of the environment in the chamber. A convenient method is to monitor the plasma that is generated inside a typical inverted magnetron Penning type vacuum gauge. A typical vacuum chamber will have one or more of such devices. The internal plasma is generated by means of an anode and cathode supported by a magnetic field. The plasma current drawn between the anode and cathode is a measure of the amount of ionized species present and hence represents the vacuum chamber pressure. The plasma emission monitoring of this plasma is a powerful means to sense the gaseous species present and hence any background gases in the chamber whilst at the same time measuring the excess process gases in reactive sputtering. As the plasma is generated remotely, the in-process plasma does not need to be present in order to monitor the chamber gas levels. This provides a method to sample background gas levels before the start of a process – intelligent switch-on, see figure 4.

As can be seen in figure 4 the gauge can detect the background hydrogen from the vacuum chamber before the process starts. The measurement of hydrogen is representative of the moisture level contained in the vacuum vessel and as can be seen in figure 5, the level on hydrogen can be monitored with time in order to determine the optimum process-on time or plasma pre-treatment conditions.

Thus it is possible to predict the exact point at which the vacuum level is ready to begin a process. Also, any changes with time can be used to predict when a vacuum chamber has developed a

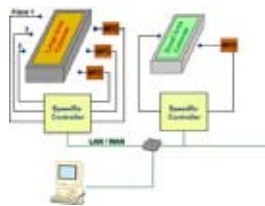


Figure 3  
Typical PEM monitoring arrangements for large area and small area magnetron cathode arrangements

leak or when the build-up of coating material on shielding has reached a level where the vacuum is becoming compromised. This is typically more relevant in batch coating units.

The plasma in the Penning Gauge is further useful in avoiding substrate effects commonly seen with in-chamber PEM. Figure 6 illustrates changes that can occur in a plasma system when the substrate moves past the magnetron plasma. The change in plasma intensity is a result of the change in the plasma impedance as either a conducting or electrically floating surface passes near or into the magnetron plasma. The plasma electrons are very sensitive to changes in the electrical potentials of surfaces around the magnetron and chamber. Hence the distribution of the plasma can change which in-turn leads to changes in the intensity measured by the fibre-optic looking at one point in the process. In such cases, this measured variation in intensity is not a 'real' change that demands a response from the MFC for the reactive gas to maintain equilibrium on the target. The plasma sensor cannot discriminate between real and false effects if it is solely monitoring the intensity of the metal or gas signal. Using a combination of signals can help to provide a better picture, as can the 'ex-situ' monitoring of the excess gas in the Penning gauge via a PEM signal.

In the area of glass coating, the issue of plasma disturbance is highly relevant. The glass is a large area of insulating surface that intermittently passes in-front of the magnetron plasma. Hence the plasma intensity will vary as the glass 'arrives' in front of the magnetron. This in combination with the pump baffling effect of the glass can lead to 'edge' or 'picture-frame' effects on the glass as a result of a slightly thicker coating around the outer extremities of the glass.

An additional problem is one of different cut glass sizes that are commonly processed in the same machine. Variation in the width of the glass further changes the effective 'anode' in-front of the plasma leading

to local plasma emission fluctuations. Hence the combination of different glass sizes and the in-line nature of the processing will disturb the stability of the PEM signal and present problems for gas and thickness uniformity control.

As previously mentioned the use of an Argon base-line signal is beneficial to filter out these effects as is the undisturbed excess gas signal from the PEM-Penning sensor.

By combining multiple in-situ and ex-situ PEM measurements the various disturbances can be removed. This will be documented in future publications.

### Effective short term feedback control from the plasma emission signal in the Penning gauge

The ex-situ signal is shown to be representative of the in-chamber gas conditions and whilst being less prone to disturbances or drifts, it has some advantages as a means to provide a process sensor for feedback control of the reactive gas. It has previously been shown that in-chamber PEM and target voltage monitoring can provide an effective high speed signal that can control a reactive process when combined with a suitable feedback algorithm such as PDF+ [3, 5]. If, the ex-situ PEM signal can also provide the same degree of control, then the addition of the new sensor increases the options available for an optimum process control solution.

Figure 7, shows a feedback control response for the titanium and oxygen system based upon the ex-situ PEM-Penning gauge method. As can be seen the gas controller can move the process between different set-points and establish effective stable control. The responses are typically the same when compared to the conventional in-situ method [3, 5]. Moving between set-points is possible without re-tuning of the algorithm parameters with the exception of the lowest set-point where the process becomes unstable. To operate at that point the PDF+ algorithm parameters would require re-tuning. It is typically not always possible to move between different set-

Figure 4

Plasma emission spectrum from inside a Penning Gauge when process plasma is off and system is pumping only

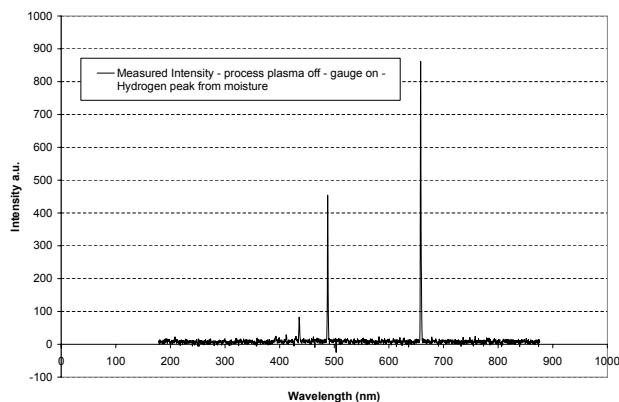
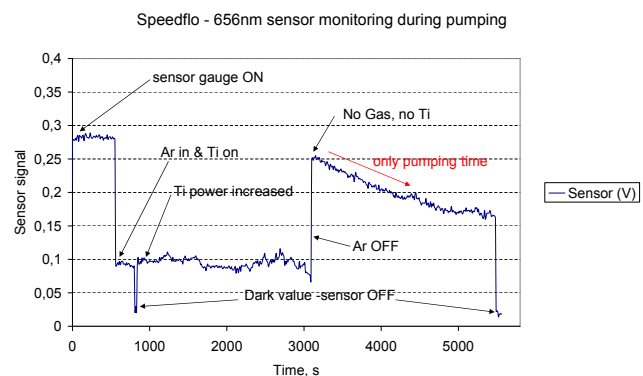


Figure 5

Change in hydrogen intensity (656nm wavelength) measured in the Penning gauge with varying plasma conditions in the chamber



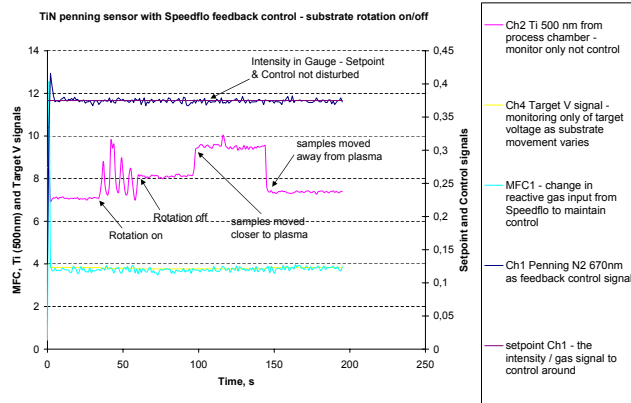


Figure 6

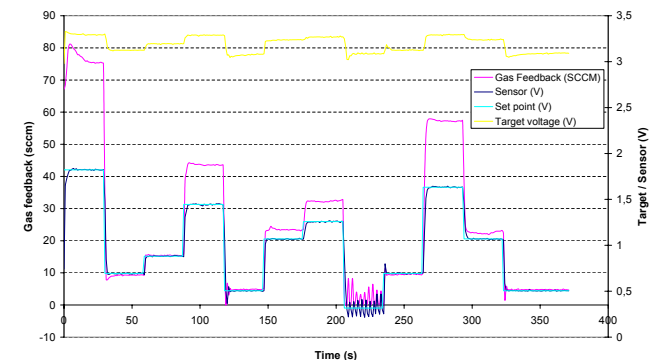
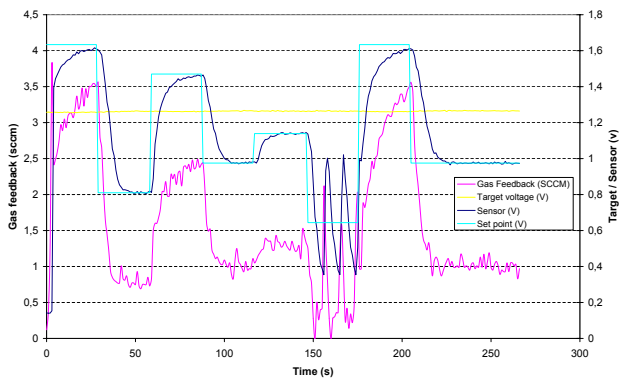
Effect of substrate movement and separation to the magnetron on plasma emission signal from the chamber and also the Penning gauge as a comparison

Figure 7

Variation in process feedback control set-point via PEM-Penning sensor for the Ti-O<sub>2</sub> system

Figure 8

Variation in process feedback control set-point via PEM-Penning sensor for the Ti-N<sub>2</sub> system



points instantly as the dynamics of the system take time to respond. Inertia is built-in as a result of the time it takes for the target to increase or decrease the amount of poisoning, i.e. sputter away the excess oxide to achieve the new state. Once the set-point has been achieved the process controller will hold it there by rapidly adjusting the gas flow via the MFC.

Figure 8 illustrates the same method to provide feedback control in a titanium – nitrogen system and confirms that PEM-Penning ex-situ method is equally effective in providing process feedback control in a similar way to the oxide process. It can be seen that the dynamics of the Ti-N system has less inertia and different set-points in the process are achieved more quickly, i.e. the target condition reacts faster.

### PEM for process control & intelligent monitoring

It has been shown that plasma emission monitoring provides much information from the process environment. This information can be used before, during and after the production process to improve the performance of a system. The potential benefits come in two main categories; reduced energy costs and enhance productivity. These can be characterized as the following:

#### Reduced Energy Costs

1. Use PEM feedback control to operate in the transition mode as opposed to a fully poisoned mode – should yield a 40-70% energy cost reduction for the equivalent deposition rates based upon lower powers and cooling requirements.

2. Reduce the time for system preparation before processing by quantifying the actual vacuum environment suitable to begin the process.
3. Use PEM based rate monitoring to balance the process and feedback set-points whilst maximizing efficiency of energy use.

#### Enhanced Productivity

1. Reduce the pre-processing time to the minimum by analyzing when the environment is ready.
2. Use feedback control to enhance and maintain rates in reactive processes.
3. Predict accurately when the system requires maintenance by continuous sensing of the environment.
4. Identify drifts and machine problems (such as moisture levels) to correct or alert when it is unsuitable to continue production.
5. Use PEM as a feedback for substrate plasma pre-treating conditions to optimize the effectiveness of moisture removal.

#### Conclusions

The data presented has illustrated that plasma emission monitoring can provide valuable data that can be used for both short term and long term benefits. The used of an ex-situ plasma from inside the Penning gauge provides a more robust signal as substrate effects and process drifts can be avoided. Also, the process environment can be sampled before the plasma process begins.

Such PEM condition monitoring has the potential to deliver cost reductions and productivity improvements. This is highly desirable for any production

process and is now the standard approach in the semi-conductor industry where strenuous attempts are made to maximize the up-time of the tools and the throughputs. It would seem natural that similar approaches are applicable for the wider PVD industrial sectors.

A good example is the large area glass industry where the large investment in off-line coating equipment and the competitive nature of the market means its is critical to maintain the processing machines in an optimum state and maximize their effectiveness in order to drive the product costs down or maximize profits. Monitoring of all stages of the plasma processing cycles will help achieve this and the different ways that PEM can be employed is a powerful tool to realize such aims.

#### Address for submission and inquiries

Questions relating to contents of the paper can be directed to dermat.monaghan@gencoia.com.

#### References

- [1] J. Chapin, C. R. Condon, US Patent 4,166,784 (1979)
- [2] S.J. Nadel, P. Greene, "High rate sputtering technology for throughput and quality", International Glass Review, Issue 3, 2001, p. 45.
- [3] V. Bellido-González, B. Daniel, J. Counsell, D. Monaghan, "Reactive Gas Control of Non Stable Plasma Conditions", Proc of ICCG, Saarbrueken, 2004.
- [4] S. Berg, H-O. Blom, T. Larsson, and C. Nender, J.Vac.Sci.Technol., A5 (2) (1987) 202.
- [5] V. Bellido-González, B. Daniel, J. Counsell, D. Monaghan, "Expanding the list of candidate materials for reactive gas control with target voltage feedback", Society of Vacuum Coaters, 49<sup>th</sup> Annual Technical Conference Proceedings (2005) ISSN 0737-5921