Sustainability Issues in Sputtering Deposition Technology

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Abstract

Sputtering involves ejection of atoms from a surface upon impingement by energetic ions generated by a plasma. The plasma is created by a large potential difference (2 kV) between the cathode and anode in vacuum and it contains both electrons and ions. These ions get accelerated towards the target (cathode) to eject the adatoms of the target that deposits onto the substrate to form a thin film. The deposition rate of sputtering depends on the plasma density; higher plasma density increases the ions involved in bombardment of the target. Like any other manufacturing process, sputtering technology is associated with sustainability aspects such as control of the plasma density, input potential voltage and current, efficiency of sputtering (sputtering yield, mean free path), cooling system (input water and cooling power), temperature (substrate and target) and maintenance of the sputtering systems. Issues of production rates, automation and mass production are also very important for sustainable manufacturing process including sputtering technology. Optimization of the process parameters for deposition of specific films should consider these sustainability issues. This article highlights these sustainable issues with an effort to evaluate the sustainability of sputtering as a thin film deposition technology using HHV TF500 Thin Film Deposition System as a case study.

Keywords
Parameters, Sputtering, Sustainable, Thin films.

1. Introduction

Sputtering process involves ejection of atoms from the source material (target) through ion bombardment and deposition of those atoms onto a substrate surface. The subsequent diffusion and condensation of the atoms onto the substrate surface result into formation of continuous films. Usually, the target is the cathode while the substrate is the anode. Sputtering is a non-thermal vaporization and non-chemical process, which means that the atoms from the cathode (target) are physically ejected and physically deposited onto the anode substrate. The process takes place inside a vacuum chamber, which is created by low pressure plasma (~ 5 mTorr) or higher plasma pressure of up to 30 mTorr. There are various parameters which affect this process, namely target and substrate material types, bias voltage, sputtering power, substrate temperature, target temperature, argon gas flowrate, reactive gas flowrates and ratios, target-substrate separation distance, substrate holder rotational speed, base vacuum, target-substrate geometry, sputtering gas pressure, etc. (Kelly and Arnell 2000) (Mwema et al. 2019) (Igasaki and Saito 1991). Figure 1 is a schematic illustration of a sputtering facility. As shown, the facility basically consists of the target and substrate holders, power sources (which may be direct current (DC), alternative current (AC), radio-frequency (RF) or high power impulse magnetron (HIPIMS)), vacuum chamber, plasma (consisting of neutral argon and ionized atoms), cooling system, vacuum pumping and sputtering gas delivery system (Simon, 2018) (Wasa and Hayakawa 1978). The system also consists of reactive gas(es) delivery systems (not shown in Figure 1). Literature on science of sputtering, generation and sustenance of plasma is available (Kelly and Arnell 2000).

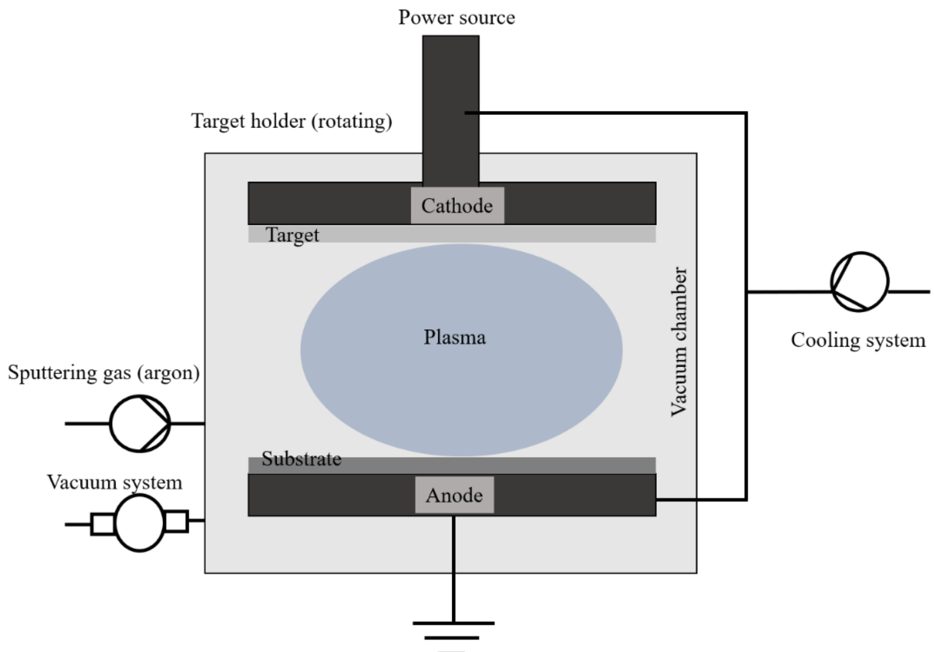

Figure 1. Main components of a sputtering facility

Deposition of thin films through sputtering process is preferred by researchers and industry over other deposition methods (see Figure 2) because it is a low temperature process, flexible (various parameters can be varied for optimized properties), better step coverage, causes less radiation damage to the substrates, possible to sputter metals, non-metals, alloys, liquids and solids (Kelly and Arnell 2000) (Shapiro et al. 1986). Additionally, compared to chemical deposition techniques, sputtering method does not have considerable emissions which may contribute to environmental pollution.

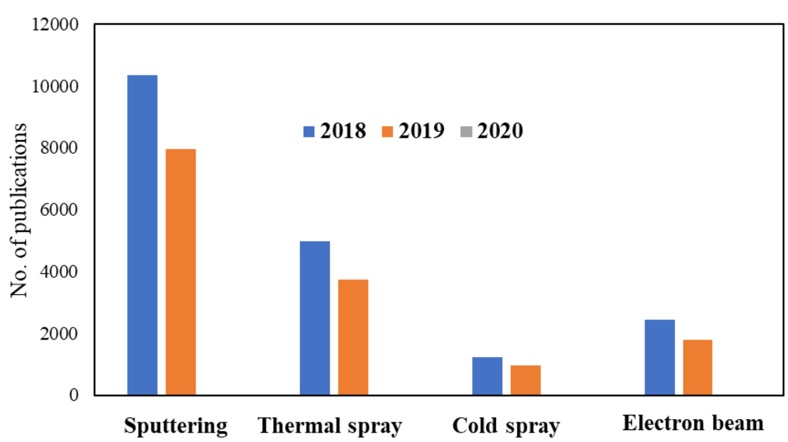

Figure 2. Summary of publications in physical vapor deposition methods according to ScienceDirect database

Considering sputtering as a manufacturing process for producing both thin and thick films for various applications, sustainability issues can not be overlooked. The focus of modern industry is on the adoption of energy efficient, less wastage, cost effective, safe and eco-friendly manufacturing systems and processes (Akinlabi and Akinlabi 2018) (Dambhare et al. 2015). Additionally, in the spirit of industry 4.0, such systems should be flexible and smart. The question at had in this case is, '*what are the topics/aspects to consider when studying the sustainability of sputtering technology as deposition method for thin/thick films?'* Figure 3 summarizes the answer to this question and the specific aspects of the sputtering process in relation to sustainability are described in the subsequent subsections. In our discussion, we shall use a case of TF500 deposition facility manufactured by HHV Ltd, UK. A picture of this facility is shown in Figure 4 and it is one of the facilities for enhanced deposition with the capability of radiofrequency (RF) reactive sputtering of large and higher number of samples and therefore can be enhanced for mass production.

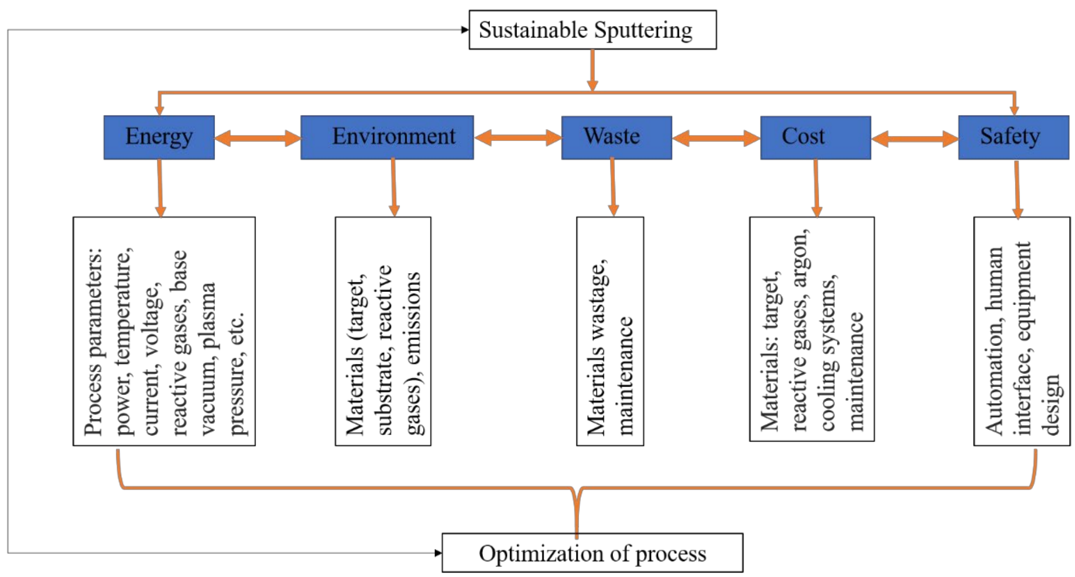

Figure 3. Sustainability issues in sputtering technology

Figure 4. A typical modern sputtering facility TF500 series manufactured by HHV Ltd, UK
(http://www.hhvltd.com/tf-500-600-800)

2. Process Parameters

As reported in literature, sputtering deposition of films depends on various process parameters some of which include temperature, power, pressure, flowrate, materials type and so forth (Mwema et al. 2019) (Shiller 1979). The quality of the films produced via sputtering is an interplay of these parameters and therefore making the process complex (Mwema et al. 2019). Besides determining the quality of the films, these parameters affect the energy utilization of the system. To achieve the required base vacuum of 10^{-5} mbar of the TF500 system, the vacuum pump of 200 W rating should be run for approximately 1 h. Within this time, there is no sputtering taking place and the power is only expended on creating a vacuum in the chamber. Creation of the plasma requires introduction of the argon gas into the chamber at a specific pressure (in the case of TF500 system, a pressure of order 10^{-2} mbar is used). Electric power is expended towards pumping of the argon and maintenance of the flowrate within the chamber. The higher the flowrate and pressure the higher the electric energy utilized by the pumps. If the pressure is too high, the mean free path of the atoms is reduced due to increased collisions resulting in lower sputtering yield. At times, to enhance the formation of the thin films, the target and/or substrates may be heated above the ambient temperatures. The TF500 system (Figure 4) has a maximum heating temperature of the substrate of 110 °C however other facilities may heat up to 600 °C. In case of RF sputtering systems such as TF500 facility, RF power plays an important role in thin film deposition. The system has a maximum RF power of 350 W. Optimization of the deposition parameters should not only focus on enhancing the quality of the films but also efficient utilization of the electric energy. Energy is also consumed in cooling systems, reactive gas delivery, rotation of the samples and pre-sputtering. As such, studies on the growth of thin films and energy utilization are necessary to enhance sustainability of sputtering technology.

3. Materials and Maintenance

For the process to be sustainable, it should be environment-friendly, safe, having minimal wastage and cost effective. In sputtering, these factors are directly affected by materials and maintenance requirements of the system. The materials required in a sputtering process include target, coolants, reactive gases, sputtering gas (argon) and substrates (Mwema et al. 2019) (Simon 2018). Sputtering can use nearly all materials as targets including liquids, metals, non-metals, alloys and compounds. From a sustainability point of view, regardless of the type of material, sputtering is a physical process and does not involve chemical reactions which may create poisonous emissions to the environment. However, there are fumes emitted during sputtering of some of target materials such as titanium carbide, aluminum as observed in the course of using TF500 system (we were forced to use mouth and nose masks during the sputtering). Mostly, the choice of the target and substrate materials is based on the desired engineering application. There is need to consider emission behavior of various target materials during sputtering. Research is necessary to document emissions levels of various targets during sputtering if sustainability of these processes is to be achieved. The use of reactive gases such as oxygen and nitrogen during sputtering should be effectively controlled to avoid unnecessary emissions within the sputtering facilities.

Another consideration is the material wastage during sputtering process. Although, it is not documented in literature, we observed a considerable loss of sputtered material to the chamber walls and other parts of the facility as shown in Figure 5.

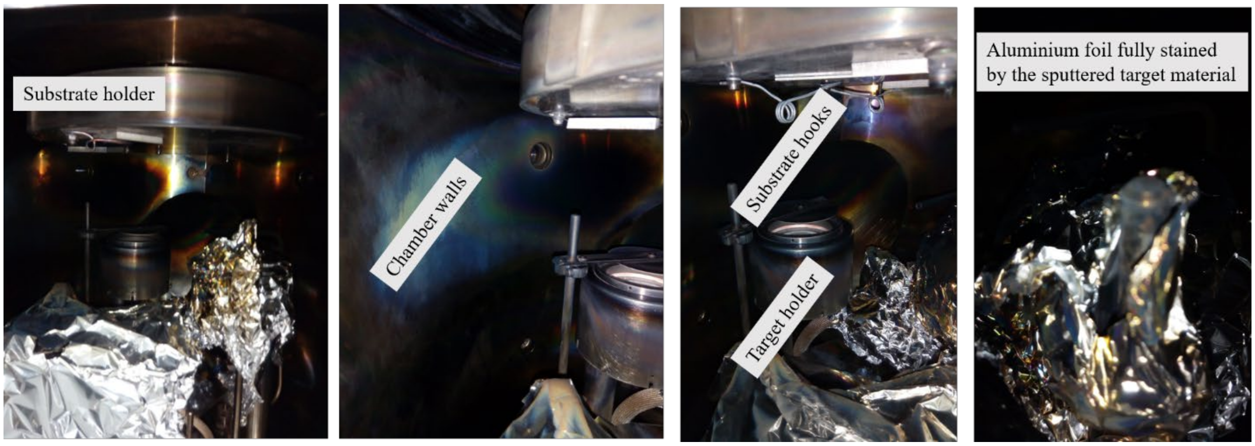

Figure 5. Stained parts of the HHV TF500 system during deposition of TiC thin films on mild steel substrates

As shown, some target material gets deposited onto the substrate holder, chamber walls and other parts of the system and therefore contributing to material wastage. For instance, during deposition of TiC on mild steel substrates on the HHV TF500 system, we wrapped the thermal spray and electron gun systems with an aluminum foil; interestingly after the process, a visible layer of the TiC material had been deposited onto the foil (see Figure 5). The attachment of the target material onto various parts of the facility pose a maintenance challenge and cost to the system. As shown in Figure 6, the target holder (cover and screws) tend to wear out faster than the rest of the parts. Additionally, the ejection of target material is not usually uniform (Figure 6), which results into further material wastage besides compromising the quality of the films. After every deposition cycle of the HHV TF500 system, the substrate hooks, target holder and cover, screws and target must be cleaned by high pressure air (Figure 7) and by acetone. Additionally, the quality of the target and substrate hooks should be checked after very cycle and replaced when necessary.

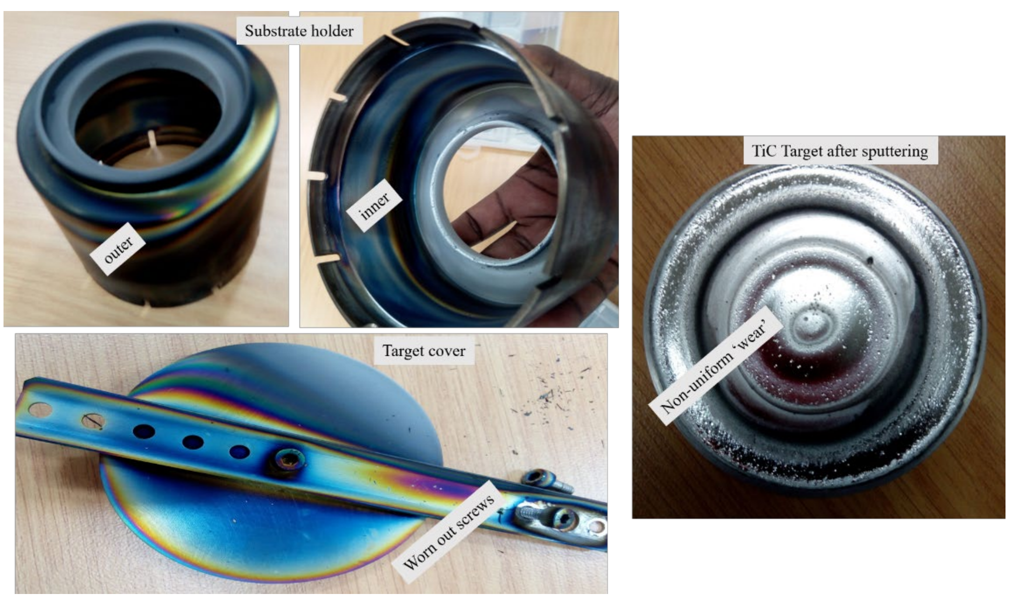

Figure 6. Worn out parts of the target holder

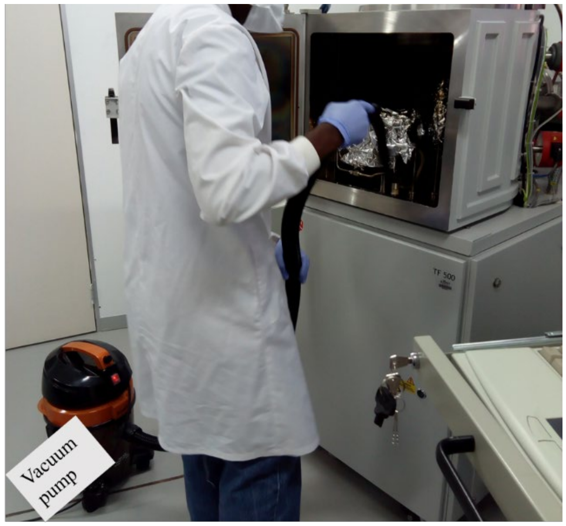

Figure 7. Vacuum cleaning of HHV TF500 system after a sputtering cycle

4. Automation and Flexibility

The preparation of the target and substrate, loading of the samples into the chamber and cleaning of the are manual processes undertaken by the operator. Most of the deposition processes such as pre-sputtering, chamber vacuum, base pressure control, time, temperature control, reactive gas and sputtering gas deliveries, sputtering power and so forth have been automated in most of the sputtering systems today. For instance, the HHV TF500 facility consists of a central processing unit (CPU) controlled through a human interface system consisting of touch screen (Figure 8) and turning knobs. Monitoring and control of the sputtering process is undertaken through this interface, making the facility safer and easier to use.

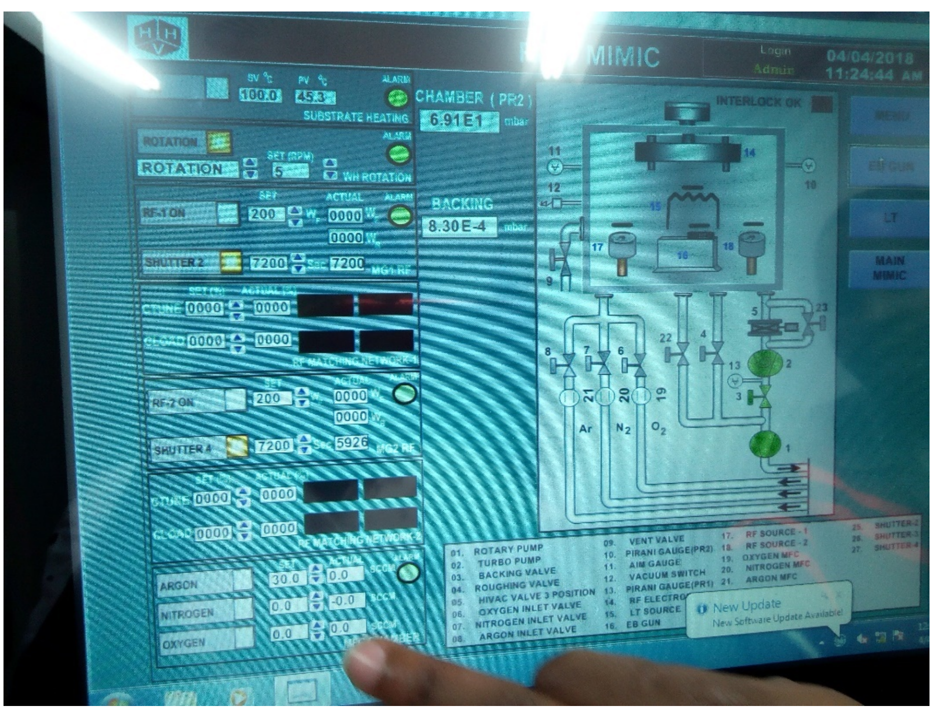

Figure 8. Human interface touch screen for control and monitoring of film's deposition on HHV TF500 facility

This means that there is less human interruption on the actual process as from vacuuming to cooling of the deposited films. The automatic control and monitoring have enhanced the routine flexibility of the sputtering processes since it is possible to combine various process parameters to achieve specific quality of thin films. For instance, by combining various process parameters (optimized), it has been possible to deposit fractal or ordered films for different applications (Mwema et al. 2018). Additionally, as stated earlier, the capability of the sputtering process to use nearly all types of target materials is an aspect of routine flexibility.

5. Conclusions

Sustainability aspects of sputtering as a novel manufacturing process of thin and thick films have been identified and described. In studying sustainability of sputtering, the following topics ought to be considered:

- The interplay between the processing parameters (pressures, power, temperature, cooling, flowrates, voltage, etc.) and the energy utilization of the facility. Optimization of the processes should also consider the energy consumption of the system in addition to the quality of the films.
- The material and maintenance of the system in relationship to wastage, safety, environment and cost. The choice of the target and substrate materials should go beyond the mere application of the deposited films-should account for safety, reduced waste, clean environment, cost effectiveness and safety.
- In line of industry 4.0, these systems are automated and exhibit routine flexibility. Machine flexibility and material handling processes should be enhanced.

Acknowledgements

We acknowledge the University Research Committee for funding the research student working on sputtering deposition of thin films.

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Biographies

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