M y involvement with sputtering began in the fall of 1973 when I was a graduate student working on my Ph.D. thesis. I had been given the problem of understanding the effect of the eta carbide layer, a ternary compound of cobalt, tungsten, and carbon, on the performance of titanium carbide coatings deposited on cemented carbide cutting tools by the chemical vapor deposition (CVD) process. With the high temperature CVD process, I was not able to reliably control the growth of the eta carbide layer that formed between the TiC coating and the substrate.

Fortunately for me, there was a small RF diode sputtering system available that I could use. I was able to deposit TiC coatings with and without the eta carbide layer and show the detrimental effect of the eta carbide on the performance of the coated cutting tool. The sputtering system that I used was not overly reliable. I spent more time fixing it than I did running it to deposit coatings, and I swore that once I finished graduate school I would never do sputtering again. Little did I know that oath was not to be.

My first job out of graduate school was to develop hard wear resistant coatings using RF diode sputtering to extend the life of forming tools. I remember when the RF diode system was being installed that the service engineer for the sputtering equipment manufacturer asked me my thoughts about the recent introduction of magnetron sputtering. He was really excited about it, and little did I know at that time that the rest of my career would center on magnetron sputtering and all of the improvements that were to come with it. The initial benefit of magnetron sputtering was that it produced on average a 10-fold improvement of the deposition rate compared to diode sputtering.

I spent many years using magnetron sputtering to reactively deposit hard wear resistant coatings for tribology applications. I was fortunate enough, with the help of a great technician, to develop closed loop control of the partial pressure of the reactive gas for high rate reactive sputter deposition of compound materials. With the closed loop process, it is possible to operate the system in what is now called the transition zone between the metallic and fully poisoned states of the magnetron target. For materials such as titanium nitride (TiN), it is possible, operating in this transition region, to deposit the TiN at the same rate as that of pure titanium. Prior to the closed loop control development, the deposition rate for TiN was only about 15% of the metal rate. High rate reactive sputter deposition opened the doors for the deposition of hard materials for many industrial applications by making the reactive sputtering process cost competitive with other deposition techniques.

Although magnetron sputtering increased the deposition rate, many magnetron deposited films did not have the density of films produced by other physical vapor deposition (PVD) processes. With the advent of unbalanced magnetron sputtering, which was given to the world by Window and Savvides [1], and the closing of the magnetic fields in multi-cathode unbalanced magnetron sputtering systems, it was possible to increase the degree of ion bombardment of the growing films during ion assisted deposition by a factor of ten [2]. With this improvement of the ion assisted deposition with closed-field unbalanced magnetron sputtering, the quality of the films match that of films produced by other PVD coating techniques, and sputtering was a viable alternative for producing well adhered, dense hard coatings.

By the late 1980s, the one thing that was missing for reactive sputtering was the ability to deposit insulating films at high rates. The issue was that if direct current (DC) power were used during the reactive deposition of a material such as aluminum oxide (Al₂O₃) there would be severe arcing on the target. Arcing usually results in droplets being ejected from the target, many of which would be trapped in the growing film. In addition, arcing could damage the power supply. This problem was solved by the introduction of pulsed DC power and mid-frequency alternating current (AC) power. Both pulsed DC and mid-frequency AC power could prevent the arcing problems on the target during reactive sputter deposition, and it was another major advancement in sputtering technology.

By the middle of the 1990s, it seemed like most of the problems associated sputtering had been solved. Sputtering was a true and tried deposition technique, and there was little or nothing left to learn about it. How wrong this assumption was. In a paper published by Kouznetsov and co-authors in 1999 [3], they described how to produce a highly ionized flux of the sputtered particles in a process that has now become known as either as high power pulsed magnetron sputtering (HPPMS) or high power impulse magnetron sputtering (HIPIMS). It is the same process for either acronym; it just depends on what side of the Atlantic Ocean that you reside as to which one you use.

The basis of HPPMS/HIPIMS is that a very large DC power pulse is applied to the sputtering target for a very short period of time. Peak power levels can reach up to 3,000 W/cm², but the duration of the pulse is only on the order of 100-150 μsec. Although the peak power is very high, the average power is in the range of typical sputtering power levels because the pulse repetition rate is relatively low. The beauty of the HPPMS/HIPIMS process is that a large fraction of the sputtered material becomes ionized. The degree of ionization of the sputtered material is dependant on the material and the peak power density, but for a material such as titanium the ionization fraction can reach 70% or greater [4].

There is one down side to the HPPMS/HIPIMS technology as practiced by the Kouznetsov approach. For an equivalent amount of power, the HPPMS/HIPIMS deposition rate is only 25-30% of the DC rate. Dave Christie [5] developed a model to explain this rate loss, and much work has centered on understanding it.

Fortunately there is a solution to the rate loss problem. It comes from a small company in Massachusetts called Zond, Inc., and they have a variation of the HPPMS/HIPIMS process called Modulated Pulse Power (MPP) [6]. The MPP process produces a multi-step pulse with pulse durations up to 2-4 msec, but it does so with less average peak power. However, it too produces a very high degree of ionization of the sputtered material, and in contrast to the Kouznetsov approach, the MPP process can actually have an increase in the deposition rate compared to the DC rate. Rates as high as twice the DC rate have been reported for several materials [7].

The promise of HPPMS/HIPIMS/MPP is that the high ion flux of sputtered material can be used to enhance film properties and to allow sputtering to be used in applications that were not possible before. Petrov et al. [8] reported that when there is a high ion to neutral ratio flux at the substrate, it is possible to deposit well adhered, fully dense films at low ion energies and with low residual stress. This means that it should be possible to deposit thick PVD hard coatings on the order of
tens of microns and not suffer delamination of the coating due to high residual stress. In addition, complex shapes can now be coated more uniformly because the ions will follow the electric field lines into the substrate when a bias is used. Evidence of the ability to deposit thick coatings and to coat complex shapes much more uniformly than previously done is now starting to emerge [9,10].

We are at a new frontier for sputtering. The HPPMS/HIPIMS/MPP technology holds great promise and, as is often the case, the technology leads the science. I will be the first to admit that I do not fully comprehend what is happening during the generation of the highly dense plasma in the HPPMS/HIPIMS/MPP process, but I can certainly see where it can be used. Just when we thought we knew everything, we find out once again that we know so little.

It is truly an exciting time to be in the sputtering business, and I look forward to being involved with the development of the HPPMS/HIPIMS/MPP technology for many years to come. There is still a great future in sputtering.

References

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