Report on the 57th Workshop of the International Union for Vacuum Science, Technique and Applications IUVSTA on High Power Impulse Magnetron Sputtering (HIPIMS)

High Power Impulse Magnetron Sputtering (HIPIMS) is a relatively new Physical Vapour Deposition technique and has been shown to produce surface coatings with improved properties, in particular in terms of film density and adhesion to a substrate. During the impulse part of the cycle power levels are extremely high, promoting exceptionally high degrees of ionisation and excitation in the plasma. Different levels of fragmentation of plasma species and greatly increased ionisation result and the substrate is bombarded with a significant fraction of ionised coating species.

One of the key factors in creating improved adhesion is the implantation of metallic species into the substrate and the grading of the interface between substrate and coating that results from the high power pulsed bombardment. Significant improvements to the morphology and microstructure of nitride and oxide films are achieved due to the high ion-to-neutral ratio, gas-ion to metal-ion ratio and reactive species activation in the HIPIMS plasma

The present state of the art indicates that this process has high potential for improved coatings. However, very little is known about the detail of the process parameters which exists in a typical HIPIMS system. This 57th IUVSTA Workshop aimed, therefore, to fill in some of the gaps in this understanding by bringing together specialists in the field and providing a forum to discuss latest results. It is anticipated that these discussions will pave the way for further successful developments and applications of the HIPIMS technique.

The Thin Film Division is very grateful to Professor Michel Hecq, Professor Rony Snyders and Dr Stephanos Kostantinidis of the Materia Nova Institute, University of Mons, Belgium, for their help in hosting this event and for arranging an excellent programme which included some useful scientific discussions and also very interesting social events. We are also grateful to, CemeCon, GfE, Hauzer, Hiden Analytical and Solvix for additional sponsorship of the Workshop.

The meeting started with a tour of the laboratory of Inorganic and Analytical Chemistry (LCIA) of the Université de Mons-Hainaut. This laboratory is active in the field of plasma-surface interactions. The research philosophy of the lab is to correlate the plasma composition and energetics to the chemistry and the microstructure of the treated surfaces. Different diagnostic tools (OES, AAS, GDMS, Langmuir probes) are used in order to gather useful information on the plasma while the treated surfaces are characterized by numerous techniques such as TOF-SIMS, XPS, SEM, TEM, and XRD. Several plasma sources are used and designed (including μ-wave, RF, DC, pulsed DC). Among them, magnetron plasmas are used in numerous projects to (reactively) sputter materials (metals, semiconductors, dielectrics). In addition to 5 lab scale chambers, the laboratory has three semi-industrial scale vacuum chambers. Recently, the lab has developed and co-patented a power supply for high-power impulse magnetron sputtering.

The main scientific part of the Workshop was divided into the principal areas of HIPIMS with each session devoted to one of these areas. A specialist in the field gave an overview and then led the discussion which included occasional contributions by other participants. This format worked rather well and led to many long discussions on latest problems in understanding the HIPIMS process and its development for industrial use. The report summarises some of these discussions.

Session 1: Plasma and Discharge Characteristics Part 1

Jaroslavl Vlcek presented his model of the magnetron discharge process which has been developed from an earlier model of Dave Christie for high power magnetron sputtering. It appears to explain the unexpected effect that the deposition rate of Ti is reduced as the discharge power increases. This is mainly due to Ti ions backstreaming to the sputter target and due to ion losses to chamber walls from the discharge.

Jean Bretagne showed that small quantities of reactive gas in a discharge change the discharge properties. More efficient ionisation is apparent in an Argon-Oxygen mixture than in pure Ar. Optical emission studies show this effect to be really quite sensitive with 1-2 sccm of O influencing the discharge system. The influence on the discharge development of electron attachment on O_2 was emphasized. In discussion it was noted that even the results obtained when no oxygen was introduced may not be those for zero oxygen presence because oxygen may be present as an impurity in the argon supply line or vacuum system.

Session 2: Arcing Problems

Mariusz Cichowlas described the new Huettinger cross-detection monitor which has now been developed which senses both initial current rise through a pre-set threshold value and voltage fall through another pre-set threshold level. The system provides better protection on the second switch-on when a hot spot may remain on the cathode and cause a second arc event. This sensor system, combined with a cable-length compensation unit (CLC) directs most of the energy back to the supply on cut-off. The introduction and costing of this new device will be available within the next few months.

Session 3: Plasma and Discharge Characteristics Part 2

Nils Brenning gave a useful overview of plasma parameters. He described the bulk plasma anomalous resistivity (discussed by *Lundin et al, 2008a*), the bulk plasma model including plasma potential and ion z motion (covered in *Brenning et al, 2008*), sideways ion acceleration by resistive waves. (see *Lundin et al, 2008b*), the ionisation region model (see *Raadu et al., 2008*), effects of gas depletion and associated with transition from HIPIMS to dc mode(*Lundin et al, 2008c*). The key plasma diagnostic methods were discussed.

Future modelling goals were then identified and are those which would provide an insight into gas depletion, ionisation fractions (both for working gas and target metal), causes of deposition rate reduction of material which may be the result of self-sputtering (sheath back-attraction), bulk plasma E fields, azimuthal resistive drag, or, a combination of these and other effects still to be identified.

Session 4: Applications

Papken Hovsepian showed examples of coatings where HIPIMS seen to have a major advantage over cathodic arc deposition as it avoids the production of droplets but still produces a high level of metal ions. Films such as CrAlYN/CrN and TiAlCN/VCN produced by HIPIMS have far better adhesion when the initial HIPIMS treatment is applied because it injects ionic species into the substrate and gives it an etch. Multilayer interfaces are much smoother when HIPIMS is used than those for UBMS films.

Session 5: Substrate pre-treatment

Arutiun Ehiasarian provided data indicating that the HIPIMS method gives a far better pre-treated surface than other deposition methods. This improved surface allows subsequent deposition with excellent crystalline matching at the interfaces - so called local epitaxial growth. It appears that an improved subsequent coating is obtained even when using conventional UBMS on the HIPIMS prepared surface. The fast etching rates and implantation of metal into the substrate are the main mechanisms promoting local epitaxial growth. The incorporation of metal into the substrate during pre-treatment helps to preserve the crystallinity of the substrate and provide a template for subsequent coating growth. The fast etching rates promote the formation of oxygen-free interfaces. The HIPIMS method allows local epitaxial growth to be obtained over several microns of area in industrial-scale production systems.

Session 5: Coating deposition Part 1

Ivan Petrov presented the results of a literature search which showed that there is an exponential increase in the number of papers on HIPIMS in recent years. He pointed out that HIPIMS appears to provide a cleaner and more reliable surface for subsequent film growth. He used Peter Barna’s in-situ TEM movie of evaporated films to illustrate that a surface free of impurities is a critical factor in determining film growth modes that result in aligned nuclei and local epitaxy rather than randomly oriented grains. Ivan presented initial data, obtained jointly with Arutiun Ehiasarian, on the effect of HIPIMS deposition mode on the microstructure of CrN films demonstrating smoothening of the growth front and film densification that is analogous to very high-plasma-density DC sputtering. The beneficial effect of the HIPIMS mode was evident even without applying an external substrate bias. A full study of the effect of HIPIMS parameters is still required to show the effects of varied current, fluxes and energies on film composition and microstructure.

A useful start to this study was provided by Stephanos Konstantinidis who used optical emission spectroscopy to study the effect of pulse width on plasma composition. As the pulse width increases from 3-15 μsec (i.e.more time for oxidation) the Ti^{+}/Ti ratio increases. The additional ion bombardment is effective as either anatase or rutile films are formed. ZnO films are denser and smoother when formed using HIPIMS when compared with for normal magnetron sputtered films.

Session 6: Coating Deposition Part 2

Ulf Helmersson discussed the possible reasons why the HIPIMS method of coating of oxides often did not have the same hysteresis problems as seen in conventional magnetron sputtering. This improvement appears to be related to the fact that during the pulse the target etching is very high and are cleaning the surface from any reactive elements, while in-between pulses, where no plasma are present, the reaction between the reactive gas and the target is low. In normal continuous sputtering a thicker reacted layer is formed due to radiation enhanced diffusion and mixing. For aluminum oxides a pulse repetition rate greater than 1kHz prevents hysteresis occurring while for CeO_x films the value must exceed 4kHz. HIPIMS also produces much better quality aluminium oxides and Kostas Sarakinos showed that titania films could be produced either in rutile or anatase form, depending on the pressure, when using HIPIMS. In addition, he showed that CrN films with a morphology spanning from columnar polycrystalline to featureless nanocrystalline can be deposited by HIPIMS when the peak target current is increased.

A study of deposition rates during HiPIMS using different magnetic field configurations was presented by Stanislav Mráz. No deposition rate enhancement was observed for the magnetic fields investigated at constant time-averaged power. Furthermore, lower HiPIMS deposition rates were measured for a highly unbalanced magnetic field focused towards the substrate as compared with rates for a conventional magnetron magnetic field. This was attributed to the higher energies per pulse dissipated in the plasma accompanied by a change in plasma chemistry. The amount of sputtered material during the pulse did, in fact, significantly increase but self -scattering prevented more efficient transport. It is suggested, therefore, that short pulses (low pulse energies) and higher frequencies should be used which would give high average powers and large deposition rates.

Further refinements were reported by John Moore who has data on a Modulated Pulse Power (MPP) system in which the first part of the pulse cycle is at low power before ramping up to high power. By applying this type of pulse to 2 magnetrons aligned in closed-field mode and, by varying the phase shift between the pulse on each magnetron, the energy distribution of ions can be varied; with a much higher energy peak being present for certain phase settings. This technique gives a further degree of freedom in selecting deposition parameters and, in some cases, the deposition rate became higher than for normal dc operation.

Session 7: Technical scale-up problems

Christoph Schiffers explained that CemeCon were already convinced of the value of HIPIMS for production of better coatings with improved uniformity, higher density and better adhesion. CemeCon now have modular systems with a current choice of 4 or 6 cathode versions designed in a modular format so that 2 of the cathodes can be HIPIMS and also a bias supply can be added for the etching step. Results for a coating on ball-nose end mills showed a marked improvement in coating lifetime for the HIPIMS version compared with the conventional coatings.

Gerhard Eichenhofer gave details of the Solvix Bias power supply for HIPIMS applications. This newly developed Bias-supply can be used for all the conventional techniques such as a magnetron-sputtering, arc-evaporation, pre-clean and ion-etching. In addition, it has the capability of handling all the requirements needed for the HIPIMS-impulses.

Roel Tietema reported that Hauzer had already integrated HIPIMS into its PVD coater range. A Patent-Pending bias solution with arc protection has been filed, enabling the bias voltage to be maintained when there is high ion current at the substrate. For industrial job-coating there are some difficult choices to make on optimum system size: the cheapest cost per coated part will be attained for a very large batch system but there is then a risk of losing many items if that batch runs into a problem. If HIPIMS is used on an average size coater for the etching stage only then the cost per component would increase by about 18% compared with conventional magnetron sputtering. However, if the etching stage is used on a cathode and the same cathode is used with an additional sputter supply during the coating stage, then the increased cost is only about 6% per component. The cost increase is anyway worthwhile because the component has a smoother surface, lower friction and, if improved lifetime can be shown, it outperforms standard baseline coatings.

Session 8: Final discussion

John Colligon presented a brief summary of the main points in all the sessions. He again expressed grateful thanks to the local team, the sponsors, participants and to IUVSTA for support of a very successful event. The Workshop Programme Committee also did a great job and its members are listed below.

Professor Michel Hecq (University of Mons, Belgium, Chair of local committee)
Professor Ulf Helmersson, University of Linköping, Sweden
Dr Arutiun Ehiasarian, Sheffield Hallam University, UK
Professor Frank Richter, TU Chemnitz, Germany
Prof. Rony Snyders, University of Mons, Belgium (local committee)
Dr. Stephanos Konstantinidis, University of Mons, Belgium (local committee)
Professor Ivan Petrov, University of Illinois, Urbana IL, 61801, USA.(Co-Chair)
Professor John Colligon, Manchester Metropolitan University, Manchester, UK (Co-Chair)

John Colligon, December 2008

Participants at the IUVSTA HIPIMS Workshop, University of Mons-Hainaut, MONS, Belgium
12-15 November 2008