A Novel Pulsed Supply With Arc Handling and Leading Edge Control as Enabling Technology for High Power Pulsed Magnetron Sputtering (HPPMS)

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ABSTRACT

Early high power pulsed magnetron sputtering (HPPMS) results are generating growing interest in the technique because it can create large numbers of both sputtered species and process gas ions. A significant flux of these ions to the substrate at low energy can result in dense equi-axed films, desirable for many applications. An experimental power supply was designed and built to investigate HPPMS. It can deliver peak powers up to 3 MW at pulse widths of 100 to 150 microseconds, up to 20 kW average power, at frequencies up to 500 Hz. Optical spectroscopy of the plasma shows ionization of the sputtered species. The amount of ionization depends on the peak power. HPPMS has been reported to deposit very thin carbon films with a measured density of 2.7 g/cm^3, quite high for sputtered carbon. The power supply has pulse leading edge control, and arc suppression capability, enabling HPPMS deposition of materials such as carbon and aluminum which are prone to arcing. With this pulsing supply the plasma goes directly from the glow to the highly ionized state without accessing the arc state. Pulse circuit and cabling considerations, electrical measurement techniques, electrical process waveforms, optical spectra, and process characteristics will be presented.

INTRODUCTION

Thin film coating technology is being called on for increasingly difficult tasks, driven in particular by advances in semiconductor and data storage technology. Ionization of the target atoms has become more important with decreasing characteristic dimensions and increasing aspect ratios. Now, there are applications which work best when a fraction of the target atoms is ionized, including semiconductor processing, tribological coatings, and decorative/functional coatings. Target material ions can be directed to the work piece by electrical or magnetic fields. This approach is already being used for cathodic arc coatings [1]. An electrical bias on the surface of the work piece can make the ions go around corners, and cover or fill features, such as trenches and vias in semiconductor devices [2-5]. An electrical bias on the surface of the work piece can set the energy of the ions reaching the surface. These ions are most likely a mixture of target material and process gas. They deliver energy, controlled by the bias voltage, to the surface of the work piece. A properly chosen bias voltage can result in dense, high quality films, and allows the film properties, such as index of refraction, extinction coefficient, conductivity, stress, and density to be tuned to match the application [6-8].

In conventional magnetron sputtering, only a tiny fraction of the sputtered target atoms are ionized, on the order of 1% or less. Multiple approaches have been taken to create plasmas with a large target material ionization. Cathodic arc systems can provide high ionization fractions, but they generate macro-particles, precluding their use in many important applications with characteristic dimensions on the order of 1 μm or smaller, including semiconductors and hard disk media and heads. The macroparticles can be radically reduced by the use of a magnetic filter. Even so, the technique is not yet widely accepted for use in semiconductor and data storage applications.

In semiconductor manufacturing, this problem has been addressed by a combination of conventional sputtering to generate target material atoms, and an inductively coupled plasma to ionize the target atoms [9].

A new technique has been developed which can generate highly ionized plasmas with essentially conventional magnetron sputtering equipment. High fractions of target material ionization have been achieved by pulsing standard magnetrons with high peak power, roughly two orders of magnitude higher than normally used [10-12]. Target material ionization has been measured experimentally, but the theoretical explanation of the detailed mechanism is still open (to the best of the authors' knowledge). Reported peak power densities, averaged over the whole target surface area, range from 1 to 3 kW/cm^2, with discharge voltages between 500 and 1000 volts. The high peak powers result in sputtering from the entire target surface, not just a small racetrack area, as is common for typical magnetron sputtering. First reported in 1999, this technique has generated a great deal of interest. So far, it has been applied in a research environment to demonstrate the concept for semiconductor via fill and hard tool coatings. This technique is especially promising for reactive sputtering of conductive compounds, such as CrN_x [13] and TiN, for cutting tool and tribological applications. It is expected that fewer macroparticles will be generated by HPPMS than for cathodic arc processes, and that the size of the macroparticles will be

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significantly smaller. This has already been confirmed in one case where droplet free films of CrN_x were deposited by HPPMS [13]. This is an important consideration for emerging dry machining applications, in which no lubricant of any kind is used in the machining process, since they may require higher quality films than those deposited by typical cathodic arc processes today.

The process is postulated to operate in an arc free region [14], however, it is unlikely to achieve and maintain arc free operation in practical material processing systems. Sputtering, even at conventional power levels, has issues with arcing, and significant effort has been expended to develop techniques for prevention and handling of arcs [15,16]. Application of sputter deposition to more and more demanding applications has required detection and active handling of arcs. Arc handling is now a standard feature of commercial sputtering power supplies. Consequently, it seems necessary to develop pulsed supply technology to deliver the required peak and average power, and to detect and handle process arcs. Existing magnetron pulsing approaches incorporating arc handling are based on fast current rise and inductive energy storage. HPPMS processes operate at low duty factors, on the order of a few percent, and high currents, up to thousands of amperes, where inductive energy storage is inefficient, due to ohmic losses in the inductor and other circuitry, and the voltage drop across the semiconductors in the circuitry. It seems necessary to develop pulsing supplies for HPPMS processes which incorporate arc handling, and which do not incorporate approaches which are fundamentally inefficient for generating high current pulses at low duty factors.

The technology for generating and delivering high peak power pulses was highly developed for driving radars during World War II, and was subsequently declassified and published [17]. It was further developed to serve laser [18,19] and high energy physics applications [20,21]. The line type pulser was developed to deliver significant pulse energy efficiently at low duty factors. It incorporated a transmission line, or a lumped element network approximating a transmission line, charged with energy which was discharged into the load. The switches used for the discharge were closing switches, such as thyratrons and spark gaps, which means they had the ability to close, but not to open when current was flowing through them. These pulsers are known for their ability to deliver high peak powers to plasma loads. Consequently, they have been widely used in high energy physics and laser applications. However, these applications have often been tolerant of arcing, and in many cases, the loads themselves were already arcs. The single mesh lumped element pulse forming network, composed of a capacitor and an inductor, has been widely used to pulse laser flash lamps, where delivery of energy and efficiency of implementation are important. However, detection and suppression of arcs is not required, since the lamp discharge is already an arc in normal operation. In contrast, material processing plasmas typically operate in a glow or abnormal glow discharge regime, such that an instability could result in formation of an arc with much higher current density. In that case, it is necessary to detect formation of an arc, and to respond appropriately. The high peak power magnetron sputtering application is a glow or abnormal glow discharge, with plasma confined in the region of the magnetron by crossed electrical and magnetic fields. As such, instabilities can develop in which the large scale discharge collapses into a small arc with high current density. Unhandled, these arcs can begin to preferentially occur in the same location, resulting in damage to both the target surface and the work piece.

The high peak power pulsed magnetron sputtering technique has great promise as a source of highly ionized target atoms. However, without arc handling, the technique is unlikely to succeed commercially. What is required is a pulser capable of high peak power, with the added capability of arc detection and arc handling. In the best case, energy remaining in the discharge circuit would be recycled to the main energy storage elements, and not be dissipated. A novel topology for this application has been conceptualized, analyzed, and realized in hardware. The resulting pulser has been successfully employed to drive sputtering magnetrons to high peak powers at low duty factors. It has also been used to generate novel process results.

DISCUSSION

What is desirable is a pulse forming approach whose peak output current can be set by capacitor charge voltage when driving a plasma load, and whose current rate of rise and peak output current are limited in the event of an arc. A resonant network, which in its simplest manifestation is composed of a capacitor and an inductor, can provide these characteristics. The basic discharge circuit, the single mesh pulse forming network (PFN), is shown in Figure 1.

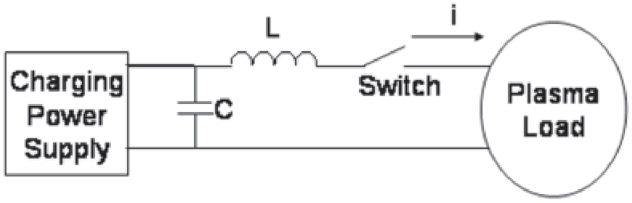

Figure l: Basic inductor/capacitor discharge circuit.

The discharge circuit must be designed considering the characteristics of the load. Material processing plasma loads typically exhibit current which is non-linear with respect to voltage and may also have dynamical characteristics which must be considered in the design of the discharge circuit. For the initial design, it may be possible to neglect dynamical characteristics and focus on the load line of the plasma. It is difficult to know *a priori* what the exact characteristics of the load will be. However, it may be possible to estimate or postulate a peak power, and perhaps estimate voltage and current at the peak power condition. This suggests a concept of large signal impedance, based on the voltage and current at the peak power condition. The simplest approach is to design the PFN to drive a resistive load having the same value as the large signal impedance. The matched load condition for the plasma is chosen such that the peak current is half the short circuit current [17]. In all cases, it is clear that the characteristic impedance of the network has a large influence on the peak current. In fact, it provides a ballast, and sets an upper limit on the output current. It is due to these characteristics that this circuit has been so widely used to drive flash lamps for photographic, stroboscopic, laser, and photo-reproductive applications.

One design approach is to fix the pulse width and calculate capacitance and inductance required for a range of characteristic impedances. As an example, Figure 2 shows the calculated capacitance and inductance for a nominal 100 μsec pulse width for characteristic impedances from 0.5 ohms to 3.0 ohms.

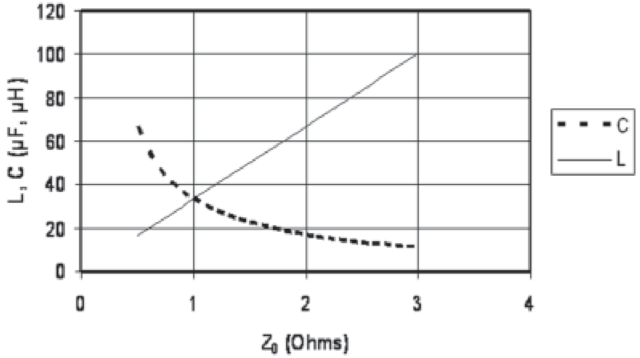

Figure 2: Capacitance (C) and inductance (L) selection for various characteristic impedances (Z_0) and a fixed 100 μsec pulse width.

One of the key considerations for the design of the pulsing circuit is current rate of rise into a short circuit. Switches for high currents and high peak power have limitations to their operational parameter space. One limitation is the current rate of rise when the switch is turning on. Another is the maximum current the switch can interrupt. In the event of operation into a short circuit, or an arc, the current will increase rapidly. If the rate of rise is not controlled, or managed, then the current may increase beyond the point where the switch is able to open without failing. The simple single mesh PFN, composed of an inductor and capacitor in series, has the ability to limit peak current and current rate of rise. It is also tolerant of additional inductance (from output cables, for example) in series with the load, since the circuit already has inductance in series with the output. So, for a typical pulse, the simple single mesh PFN discussed in this section will be suitable. However, without additional circuitry, it will be unable to effectively handle an arc in the plasma processing load. Arc handling requires that the power source be disconnected from the load to limit arc energy and arc related damage to the target and workpiece, and to extinguish the arc. It is important to minimize output cable inductance, since energy stored in the cable inductance may be delivered to a process arc.

EXPERIMENT CONDITIONS

An experimental pulsed power supply for HPPMS was built based on the principles discussed so far in this paper. The operating capabilities of the power supply are: pulse width nominally 100 to 150 μsec, pulsing frequency single shot to 500 Hz, PFN characteristic impedance 0.5 to 3.0 Ω, capacitor charging voltage 500 to 3000 V, pulse current up to 3200 A, and average power in excess of 15 kW. The unique feature of this capacitor discharge power supply is arc handling, which is a key technology for the practical application of HPPMS to industrial processes.

The experimental pulsed supply system is shown in Figure 3. The pulser rack holds the high power switch assembly, discharge capacitor bank, and discharge inductor. Selectable discharge capacitance is provided by the capacitor bank. The capacitance can be varied from 10 μF to 60 μF in 10 μF steps. The discharge inductor has several taps, with choices ranging from about 20 μH to 120 μH. An ignition circuit is also incorporated in the pulser rack. It is essentially a small capacitor, less than 1 μF, in series with a few ohm resistor. The capacitor forms a ringing circuit with the discharge inductor, which results in a well defined voltage overshoot when operated into an open circuit, such as a plasma chamber prior to ignition. This voltage overshoot helps to ignite the plasma. The resistor serves to damp the ringing of the output voltage and also to set the magnitude of the voltage overshoot. With no damping resistor, the voltage would overshoot to twice the discharge capacitor charge voltage. With heavy damping, overshoot could be eliminated. An intermediate approach, employed here, is to choose the resistor such that the voltage overshoot reaches about one and a half times the charge voltage, and the ignition waveform rings for just a few cycles. The control chassis provides power and control signals to the pulser rack. It generates the signals required to control the high power switches for both typical pulse discharges and for the arc handling sequence. Switch control signals are transmitted to the pulser rack over fiber optic cables. The control chassis incorporates the logic circuitry required to detect arcs based on both current rise and voltage collapse, and to perform the arc handling sequence. The capacitor charging supply is a 3 kilovolt ion source power supply which has been modified for capacitor charging service. Repetitive capacitor charging typically requires that the power supply first operate at its current limit, and then at its power limit, until the charge voltage set point is reached. At that point, the power supply must shut off essentially instantaneously. Then, when the capacitor is discharged, the power supply must automatically recharge the capacitor as just described. The experimental pulsed power system has operated flawlessly, with no failures, for more than fifteen months.

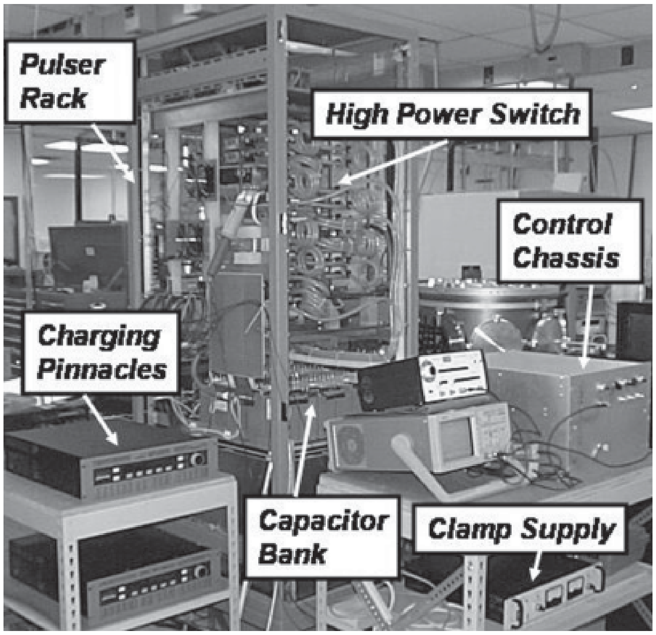

Figure 3: Experimental HPPMS pulsed power supply system.

Data were generated in two separate systems. Lower current data were generated with a medium sized, cylindrical (0.76 m diameter x 0.46 m deep) vacuum chamber with a single 0.15 m Torus 10 balanced-field magnetron fitted with an aluminum target. High current data were generated with a larger volume (1.22 m x 0.91 m x 0.76 m) chamber with a 0.30 m x 1.12 m planar magnetron fitted with an aluminum target. Process gas flow was controlled with mass flow controllers. Both chambers were turbomolecular pumped to base pressures below 7×10^{-4} Pa (5×10^{-6} Torr) prior to experimental runs. Magnetron current was measured with a Pearson model M1423 current probe and voltage was measured with a Tektronix model P6015 20 kilovolt high voltage probe.

EXPERIMENT RESULTS AND DISCUSSION

Initial plasma testing was accomplished on the large magnetron with the pulser configured for a nominal 0.5 Ω impedance. The objective of these initial tests was to verify operation of the pulser driving a magnetron at high peak power and close to maximum average power. Both plasma ignition and arc handling were evaluated in these tests. Waveforms for a typical pulse with no arcing are shown in Figure 4. In particular, there is no sign of arcing at the beginning of the pulse. The voltage never collapses to near zero (or, a few tens of volts), which would be an observed effect of an arc. The built-in ignition circuit provides a voltage overshoot at the beginning of the pulse which serves to ignite the plasma. The capacitor rings with the discharge inductor to generate a peak voltage higher than the initial discharge capacitor voltage and to define the maximum voltage rate of rise. The resistor damps the ringing and serves to limit the peak amplitude of the initial voltage spike. This amounts to pulse leading edge control. The peak current of the pulse was 1350 A at a discharge voltage of 500 V, corresponding to a peak power of about 675 kW. The initial voltage waveform rings at a frequency of about 50 kHz and the amplitude of the ringing decreases quickly due to the resistive damping built into the ignition circuit. Power density in this case is estimated at 0.5 kW/cm^2, which is approaching the 1 kW/cm^2 level where the onset of significant ionization is expected to occur [10-13]. Peak power and magnetron target area are used to estimate power density. The entire magnetron area was used because at high peak powers, the magnetron plasma tends to spread and cover the surface of the magnetron target. Waveforms of the power supply responding to an arc at the same process conditions are shown in Figure 5. When the arc occurs the voltage falls, but current stays relatively constant. The arc occurs at the peak current in this case, however, arcs were observed to occur at almost any temporal position within the pulse. The major point of testing on this large magnetron was to verify the ability of the pulser to light and drive a magnetron plasma at high current, and to handle arcs occurring during high peak power operation of the magnetron.

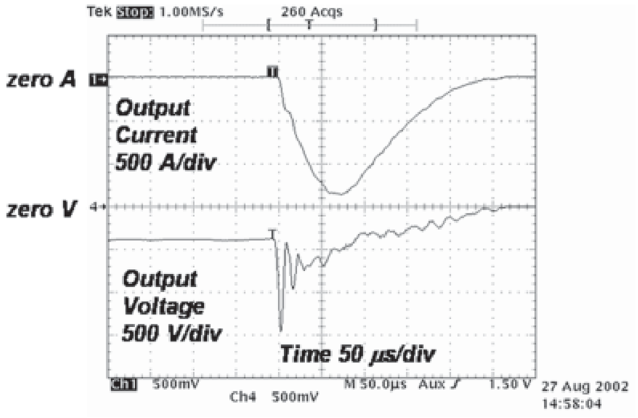

Figure 4: Oscilloscope photo of typical operation into a large (0.30 m by 1.12 m) magnetron.

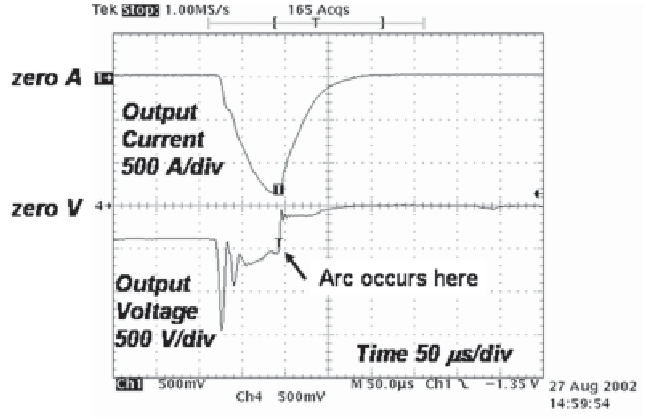

Figure 5: Oscilloscope photo of arc handling into a large (0.30 m by 1.12 m) magnetron.

Additional testing was performed with the Torus 10 magnetron. In this case, the pulser was configured for a nominal 3.0 Ω impedance. Waveforms for typical operation at lower current are shown in Figure 6. Again, there is no sign of an arc at the beginning of the pulse, since the voltage never collapses to near zero, or a few tens of volts. Leading edge control, described above, is expected to reduce the tendency of the process to arc. The peak current of 450 A occurs at a discharge voltage of 900 V corresponding to a peak power of 400 kW. This corresponds to a power density of 2.5 kW/cm^2, well above the 1 kW/cm^2 level where significant ionization is expected to occur [10-13]. Power density was estimated using peak power and magnetron target area, since the plasma was observed to spread over the whole surface of the target. The surface wear, or “racetrack” pattern on the magnetron target also indicated that sputtering occurred over the entire surface of the target. Arc handling waveforms at the same process conditions are shown in Figure 7. The voltage falls when the arc occurs, however, in this case, the current jumps. This current jump is attributed to energy in the ignition circuit capacitance being discharged into the arc through the ignition circuit damping resistor.

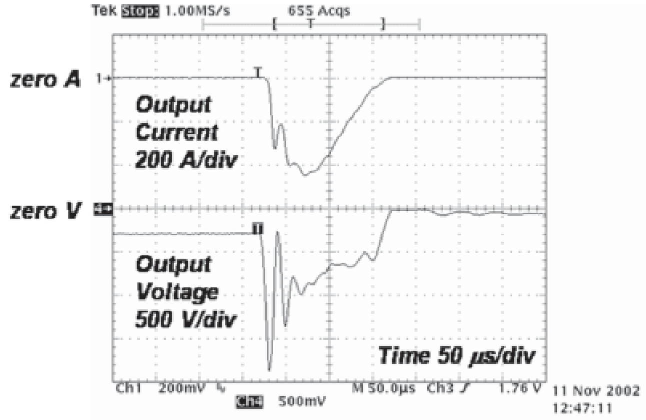

Figure 6: Oscilloscope photo of normal operation into small (0.15 m) magnetron.

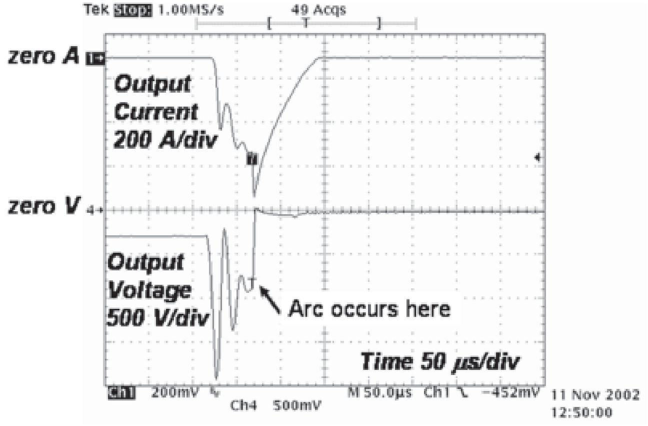

Figure 7: Oscilloscope photo of arc handling into small (0.15 m) magnetron.

It has typically been necessary to begin a process run with a conditioning cycle, in which peak power is gradually increased. Sometimes, it can take several hours to complete target conditioning. Arc handling has been essential for successful target conditioning, since the arc frequency can be quite high at the beginning of target conditioning, where arcs have even been observed in every pulse.

Temporally and spectrally resolved plasma optical emission data shown in Figure 8 provide evidence of target material ionization. The data show that the time-resolved series is dominated by strong resonant lines of Al I at 394.4 and 396.1 nm, and $4d\,^3D - 7f\,^3F^0$ lines of Al II in the neighborhood of 459 nm. The contribution of Ar II is very small, and is mainly observed at the beginning of the pulse. The isolated presence of Ar II lines at later times is observed in shots where arcing has occurred. The delay between the rise of the current pulse and the rise of the intensity of the different spectral Al lines was observed to be within the temporal resolution of our sampling (2 μs), in contrast with reports from other authors of a noticeable delay between the current pulse and the evolution of the spectral lines from metal atoms [11]. The fast dominance of the aluminum can be attributed to a combination of its low ionization potential (5.985 eV as opposed to 15.8 eV for Ar), and a possible reduction in the working gas density close to the target. A detailed explanation of the spectral evolution of these pulsed plasmas is still open.

SUMMARY AND CONCLUSIONS

An experimental power supply was designed and built to investigate HPPMS. It can deliver peak powers up to 3 MW at pulse widths of 100 to 150 microseconds, up to 20 kW average power, at frequencies up to 500 Hz. Optical spectroscopy of the plasma shows ionization of the sputtered species. The power supply has pulse leading edge control, and arc suppression capability, enabling HPPMS deposition of materials such as carbon and aluminum which are prone to arcing. With this pulsing supply the plasma goes directly from the glow to the highly ionized state without accessing the arc state. The combination of arc handling and leading edge control is expected to enable HPPMS processes not otherwise possible.

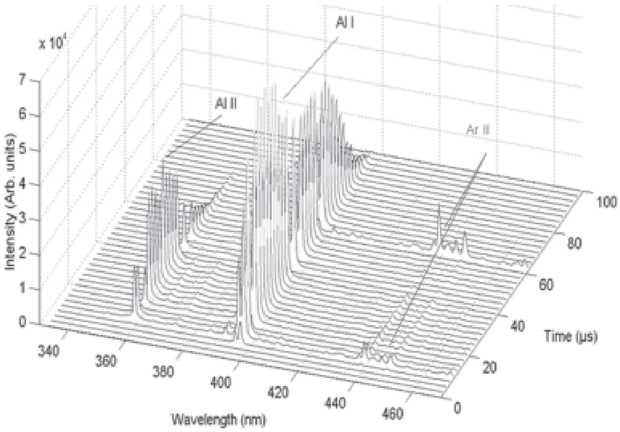

Figure 8: Optical emission spectrum for HPPMS sputtering of Al. Al I is emission from Al neutrals, Al II is emission from singly ionized positive Al ions, and Ar II is emission from singly ionized positive Ar ions.

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