Dependence of ion current on magnetic unbalancing in high power pulsed magnetron glow discharge

K Azuma and Y Inoue
Department of Electrical Engineering and Computer Sciences, University of Hyogo, 2167 Shosha, Himeji, Hyogo, Japan
E-mail: easter11_azuma@mem.iee.or.jp

Abstract. A high-power pulsed sputtering (HPPS) discharge is able to generate high ionization metallic plasma by applying a negative high voltage pulse-train with low duty ratio and high current capacity to a sputtering target. If HPPS discharge technique is applied to unbalanced magnetron sputtering (UBMS) system which is one of the ionized sputtering, we will get the metallic plasma ionized more. The ion current of direct-current UBMS increases with increase in magnetic un-balancing. However, high-power pulsed UBMS does not necessarily have the same characteristics as dc-UBMS. We investigated a connection between the ion current to a collector electrode and the number of peripheral magnets in the sputter target. The collector current increased with increase in the number of the magnets, but the ratio of the collector current to the target current depended more strongly on average input power than that for dc-UBMS. It was found that the current ratio indicated the maximum of 18.8% at the input power of 400 W in the hpp-UBMS with the peripheral 10-magnets.

1. Introduction
The sputtering deposition is one of the technologies that cover the surface of a substrate with functional thin film. It is known as the deposition process to able to form dense thin film. Especially a magnetron sputtering process has high deposition rate. The planar-type magnetron sputtering method was originally developed in 1974. A closed magnetic field is formed near the planar magnetron target by arranging permanent magnets on the backside of the target. High-density plasma is then only formed near the target by capturing secondary electrons in the magnetic field. The ions generated in the plasma are then accelerated toward the target to sputter the target material. Planar magnetron sputtering has a faster deposition rate than sputtering in the absence of a magnetic field. However, there is a drawback of low ionization-rate of the sputtered metallic species. A UBMS (unbalanced magnetron sputtering) [1, 2] can be used to improve the ionization rate compared to the traditional planar magnetron sputtering system. Another technique of raising the ionization rate of metallic plasma is a method of applying a high-power pulsed sputtering (HPPS) discharge. The HPPS discharge is able to generate high ionization metallic plasma by applying a negative high voltage pulse-train with low duty ratio and high current capacity to a sputtering target. This can be applied to the various sputter targets. A magnetron sputter target applied with HPPS technique is called HPPMS (high-power pulsed magnetron sputtering) or HiPIMS (high-power impulse magnetron sputtering) that was reported in 1999 [3]. Of course, it has been studied that HPPS discharge is applicable to the UBMS (for instance [4, 5]). If HPPS technique is applied to UBMS, we will get the metallic plasma more ionized using hpp-UBMS (high-power pulsed UBMS) than dc-UBMS (direct-current UBMS).
Commonly, the ion current of dc-UBMS increases with increase in magnetic un-balancing. However, hpp-UBMS does not necessarily have the same characteristics as dc-UBMS. In this study, we made the sputtering target electrode into which the number of the peripheral magnets was changed, and investigated a connection between the collector ion current and the number of the peripheral magnets in the sputter target.

2. The experimental setup

Figure 2 shows the experimental setup of the hpp-UBMS (high power pulsed unbalanced magnetron sputtering) system. The magnetron target consisted of the sputter target, the heat sink and the permanent magnets. The heat sink made from a circular plate of copper had the center hole in diameter of 14 mm and the torus channel in inside and outside diameters of 50 mm and 78 mm. One permanent magnet was inserted into the center hole. The others were inserted into the torus channel equiangularly. The magnets were NdFeB magnets (Niroku seisakusho Co., NE062, Ø14×17). A titanium sputter target with diameter of 70 mm and thickness of 5 mm was bolted to on the heat sink. The distance from the magnet surface to the target surface was 7 mm. The vacuum chamber had an inner diameter of 310 mm and a height of 300 mm. The sputter target was set on the upper flange of the chamber and the collector electrode with diameter of 80 mm was inserted from the bottom flange. The distance between the sputter target and the collector electrode was 100 mm. The evacuation system consisted of a turbo molecular pump (TMP, 350 L/min) and a rotary pump. The inlet gas pressure was controlled by a mass flow controller. The argon gas was introduced from behind the sputter target. The pressure inside of the vacuum chamber was measured using a ceramic capacitance manometer (ULVAC, GM-2001/CCMT-10A) and an ionization gauge (ANELVA, MIG-430/MG-2).

Figure 2 shows the experimental setup of the hpp-UBMS (high power pulsed unbalanced magnetron sputtering) system. The magnetron target consisted of the sputter target, the heat sink and the permanent magnets. The heat sink made from a circular plate of copper had the center hole in diameter of 14 mm and the torus channel in inside and outside diameters of 50 mm and 78 mm. One permanent magnet was inserted into the center hole. The others were inserted into the torus channel equiangularly. The magnets were NdFeB magnets (Niroku seisakusho Co., NE062, Ø14×17). A titanium sputter target with diameter of 70 mm and thickness of 5 mm was bolted to on the heat sink. The distance from the magnet surface to the target surface was 7 mm. The vacuum chamber had an inner diameter of 310 mm and a height of 300 mm. The sputter target was set on the upper flange of the chamber and the collector electrode with diameter of 80 mm was inserted from the bottom flange. The distance between the sputter target and the collector electrode was 100 mm. The evacuation system consisted of a turbo molecular pump (TMP, 350 L/min) and a rotary pump. The inlet gas pressure was controlled by a mass flow controller. The argon gas was introduced from behind the sputter target. The pressure inside of the vacuum chamber was measured using a ceramic capacitance manometer (ULVAC, GM-2001/CCMT-10A) and an ionization gauge (ANELVA, MIG-430/MG-2).

Figure 1. The experimental setup.

The negative high voltage pulse-train was generated by an IGBT (Insulated Gate Bipolar Transistor). The sputter voltage source, and the pulse duration and repetition rate were controlled by the driving signals to the
IGBT. The collector electrode was connected to a negative bias voltage source (−50V, 3A) with parallel-connected capacitor (40 μF, 275 V). The target current, $I_T$, through the circuit was observed using a current transformer (Pearson type 110A). The target voltage, $V_T$, was observed using a voltage probe (Tektronix, type 5100). The collector current $I_C$ was observed using a current transformer (Tektronix, P6021). These waveforms were monitored with an oscilloscope (Tektronix, TDS3034B). The skew of the current signal caused by the frequency property of the current transformer was corrected by software processing. In the case of driving the sputter target with only the dc power source, the target voltage, the target current and the ion current were measured by three digital multimeters.

The plasma was generated at the gas pressure of 0.5 Pa and the gas flow rate of 15 sccm. The negative voltage pulse-train (a set-up voltage of $-800$ V, a pulse duration of 100 μs and a repetition rate of 500 Hz) was applied the titanium sputter target. The bias voltage of −50 V was applied to the collector electrode. A floating voltage of the collector electrode was $-10$ V to $-20$ V. Therefore, the collector current observed was the ion current.

3. Results

3.1. Electrical characteristics of dc-UBMS

Figure 2 shows the current-voltage characteristics of the sputter target by driving the direct-current power source at the various number $n$ of the peripheral magnets. $I$-$V$ curves of $n = 6$ and $n = 7$ were completely different from those of $n = 8$ and $n = 10$. It is thought that the non-uniformity of the magnetic field in the circumferential direction has influenced the discharge at $n < 8$. The $I$-$V$ curves of $n = 6$ and $n = 7$ were saturated at the range greater than $V_T = 460$ V and $V_T = 500$ V, respectively. When eight or more magnets were arranged on the outside zone, the target current $I_T$ grew rapidly with increasing the target current $V_T$. In the case of $n = 8$ and $n = 10$, $I_T$ was expressed by empirical composition with base $V_T$ and exponent 7.34 $\pm$ 0.07 and 8.55 $\pm$ 0.23 respectively.

![Figure 2](image)

Figure 2. The current-voltage characteristics of the sputter target with $n$-magnets by driving the direct-current power source.

3.2. Electrical characteristics of hpp-UBMS

Figures 3 show waveforms of (a) target voltage, $V_T$, (b) target current, $I_T$, and (c) collector ion current, $I_C$. The setup voltage $-V_s$, the pulse duration $\tau$ and repetition rate $f$ of the applied negative voltage pulse-train were $-800$ V, 100 μs and 500 Hz respectively. In the case of 8-magnets, the target voltage $-V_T$ reached $-800$ V just after a pulse voltage was applied to the target and began to decrease after less than a several microseconds. The target current $I_T$ grew rapidly, but its growth rate slowed down after 14 μs. The peak value of was 72 A at $t = 28$ μs after the turn-on time. The target voltage gradually decreased, followed by a stationary state. This is for a voltage drop caused by series resistance $R_s$. When the target current reached a peak, the target voltage indicated about $-470$ V. Then, the target current decreased slowly. At the turn-off time of 100 μs, $I_T$ and $V_T$ became 51 A and $-540$ V,
respectively. The collector ion current $I_C$ continued to grow until about the time of 57 µs and was saturated with 5.6 A. After the turn-off of the voltage pulse, the collector ion current was decayed more slowly than the target current. In the case of 8-magnets, the target current grew up more rapidly than in case of 10-magnets and reached the peak of 80 A at $t = 26$ µs. At the turn-off time, $I_T$ and $V_T$ became 69 A and −460 V, respectively. The collector ion current $I_C$ reached the peak of 9.7 A at $t = 68$ µs. After this, the ion current decreased slowly. At the turn-off time, $I_C$ was 8.6 A.

3.3. Dependence on the magnetic unbalancing

Figure 4 shows the unbalance coefficient dependence of (a) the peak target current $I_{T,peak}$ and the peak collector ion current $I_{C,peak}$ and (b) the peak input power $P_{T,peak}$ and the average input power $P_T$ at the setup voltage of −800 V. The coefficient of unbalance $K$ is the ratio of magnetic fluxes from the central and peripheral magnets on the target surface [5]. In our system, $K$ is nearly equal to the number $n$ of the peripheral magnets because all of the central 1-magnet and peripheral $n$-magnets are the same material and the same proportion. The distance from the target surface to a magnetic null point at $n = 6, 8$ and 10 is 18.9 mm, 16.6 mm and 13.5 mm, respectively.

The average input power $P_T$ is the value which carried out the time average of the instant electric power $p_T(t) = V_T(t) \times I_T(t)$ supplied to a plasma source, and is denoted by the following formula:

$$P_T = f \int_0^{T/f} p_T(t) dt$$  \hspace{1cm} (1)

where $f$ is the repetition frequency of high-voltage pulses. At $n \geq 8$, The $I_{C,peak}$, $P_{T,peak}$ and $P_T$ all barely depended on $n$, and were about 80 A, 35 kW and 1.5 kW respectively. In contrast, the collector ion current $I_{C,peak}$ increased from 5.6 A to 9.7 A with increase in $n$ from 8 to 10-magnets. It was confirmed that larger ion current can be obtained by raising the magnetic unbalancing.

Since hpp-UBMS is pulsed discharge, the electrical properties of it cannot be directly compared with dc-UBMS. Then, we introduce the amount of charges which passes an electrode per unit time, $Q$. $Q$ is given by the following formula:

$$Q = f \int_0^{T/f} i(t) dt$$  \hspace{1cm} (2)

where $i(t)$ is the instantaneous current detected the electrode and $f$ is the repetition rate of the pulse-train. This is exactly the average current of $i(t)$. $Q$ is not the electric current strictly in electric engineering. Here, since we would like to discuss the quantity of the ions which reaches a collector electrode, we think it is appropriate to compare $Q$ of hpp-UBMS with $I$ of dc-UBMS.
The input power dependence of the ratio of $I_C$ to $I_T$ is shown in Figure 5. Figure 5 (a) and (b) show $I_C/I_T$ in dc-UBMS and and $Q_C/Q_T$ in hpp-UBMS. The subscripts $T$ and $C$ express the target and collector electrode, respectively. $I_C/I_T$ reached the peak at $P_T \approx 100$ W and decreased with increase in $P_T$ to about 1.3 kW. $I_C/I_T$ decreased with increase in $P_T$ and increased with increase in $n$. But, $I_C/I_T$ became independent from $P_T$ with increase in $n$. The plasma generated by sputtering is high density near the target, and lower density near the collector electrode. When electric power becomes low, an ion sheath on the collector electrode will become thick and a potential difference of the sheath becomes large. For this reason, when electric power is small, $I_C$ becomes large relative to $I_T$ in the case of low $P_T$, otherwise it becomes smaller. When $n$ becomes large, the density of the plasma near the collector electrode will become higher and the ratio of $I_C$ to $I_T$ stops being dependent on $P_T$. On the other hand, the curve of $Q_C/Q_T$ reached the peak at $P_T \approx 400$ W and approached more precipitously with increase in $n$. When $n$ becomes large, a ratio of $Q_C$ to $Q_T$ not only becomes large but it will be strongly dependent on $P_T$. Such a characteristic of $Q_C/Q_T$ may be related to how depending on which plasma spreads. The pressure of plasma will become high when $P_T$ becomes large enough. The plasma pressure increases the cross section of a plasma flow. When the cross section of plasma flow becomes larger than a collector electrode, the ratio of $Q_C$ to $Q_T$ will fall. This guess is backed up by the fact that $P_T$ at maximum point of $Q_C/Q_T$ - $P_T$ curve decreases with increase in $n$. At $n = 10$, the peaks of $I_C/I_T$ and $Q_C/Q_T$ were 17.2% and 18.8%, respectively. Generally, dc-MS is operated with the power flux density of 10 W/cm$^2$ on the sputter target [7]. When it is converted by our system, the input power is about 200 W. In terms of the improvement of the ionization due to the ion current by applying HPPS technique, hpp-UBMS should be operated with several-fold power of dc operation. These experimental results have suggested that the behavior of the ion current differs considerably in dc-UBMS and hpp-UBMS.

4. Conclusions
We investigated a connection between the ion current detected at the collector electrode and magnetic unbalancing of hpp-UBMS. The magnetic unbalancing was realized by changing the number of peripheral magnets in the sputter target. The ion current increased with increase in the number of the magnets, but, the ratio of the collector ion current to the target current depended more strongly on the average input power than dc-UBMS. When the number of peripheral magnets is eight or more, the peak input power, the average input power and the peak of the target current all barely depended on the number of magnets and indicated about 35 kW, 1.5 kW and 80 A. In contrast, the peak value of the collector current increased from 5.6 A to 9.7 A with increase in 8 the number of magnets from to 10. The ratios of the collector current to the target current with 10-magnets in dc-UBMS and hpp-UBMS...
had the peak of 17.2% at the input power of 100 W and 18.8% at 400 W respectively. It is suggested that the behavior of the ion current differs considerably by dc-UBMS and hpp-UBMS.

References
[1] Window B and Savvides N 1986 Unbalanced dc magnetrons as sources of high ion fluxes Journal of Vacuum Science & Technology A 4 (3) 453–456
[2] Savvides N and Window B 1986 Unbalanced magnetron ion-assisted deposition and property modification of thin films Journal of Vacuum Science & Technology A 4 (3) 504–508
[3] Kouznetsov V, Macák K, Schneider J M, Helmersson U and Petrov I 1999 A novel pulsed magnetron sputter technique utilizing very high target power densities Surface and Coatings Technology 122 (2–3) 290–293
[4] Vlček J, Kudláček P, Burcalová K and Musil J 2007 High-power pulsed sputtering using a magnetron with enhanced plasma confinement Journal of Vacuum Science and Technology A 25 (1) 42–47
[5] Mishra B, Moore J J, Lin J and Sproul W D 2010 Advances in Thin Film Technology through the Application of Modulated Materials Science Forum 638–642 208–213
[6] Svadkovski I V, Golosov D A and Zavatskiy S M 2002 Characterisation parameters for unbalanced magnetron sputtering systems Vacuum 68 (4) 283–290
[7] Anders A 2010 High power impulse magnetron sputtering and related discharges: Scalable plasma sources for plasma-based ion implantation and deposition Surface and Coatings Technology 204 (18–19) 2864–2868

Figure 5. The input power dependence of the ratio of the collector ion current to the target current $I_C/I_T$ and $Q_C/Q_T$ in the cases of (a) dc-MS and (b) hpp-MS.