

# Deposition Rates of High Power Impulse Magnetron Sputtering

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## Abstract

High power impulse magnetron sputtering (HIPIMS) is seen by many as the new paradigm in sputtering. It provides significant self-ion assistance to film growth. However, many noticed that deposition rates are reduced, often to less than 50%, compared to direct current (DC) sputtering rates at the same power input. It is argued here that the reduction is based on the physics of sputtering and self-sputtering, and it should not come as a surprise. Four effects can be distinguished (i) the yield effect caused by the less-than-linear increase of sputtering yield with ion energy, (ii) the impedance effect, influencing what fraction of the target-anode voltage drops in the sheath, (iii) the species effect associated with a change of ions causing sputtering, and (iv) the return effect associated with flux splitting in self-sputtering. The paper is completed by considering some business implications, in particular; it is argued that HIPIMS is a different technology and that its value should be judged comprehensively, not just by rates. Finally, the special case of temperature dependent sputtering is considered, which in some cases may lead to rates exceeding the DC rates.

## 1. Introduction

High power impulse magnetron sputtering (HIPIMS), a.k.a. high power pulse magnetron sputtering (HPPMS), is an interesting addition to the family of sputtering technologies [1-5]. It is characterized by a very high power density at the target, exceeding “conventional” power densities by about two orders of magnitude. Of course, such “abuse” of a magnetron would overheat the device if the duty cycle was high, and therefore HIPIMS is used with low duty cycles. The main motivation for using the extreme power density is the ionization of the sputtered material, which opens significant opportunities for substrate-coating interface engineering [6] and tailoring film growth and resulting properties [7].

While technologists are excited about new process parameters that have the potential of improved film quality and adhesion, many noticed that the deposition rate, normalized to the average power, is substantially reduced under most circumstances [7]. Since deposition rates are important for productivity, and ultimately for profitability, this observation is of great concern. Therefore, a closer look at the root causes for decreased rates is appropriate. This task will be done from two points of view, namely the physicists’ view and the technologists/business view. The former will emphasize the science of sputtering, and the latter what is the right approach of evaluating HIPIMS technology.

## 2. The Physicist’s view

The deposition rate is commonly expressed as film thickness deposited per unit time for a given power and geometry. To compare pulsed systems with continuously operating systems, one typically chooses to average the power over time, and of course it

is understood that the deposition rate and all other parameters vary vastly during the deposition process. That is, the average power is

$$\bar{P} = \int_0^{t_D} I(t)V(t)dt / t_D \quad (1)$$

where  $t_D$  is the total deposition time, and  $I(t)$  and  $V(t)$  are the time-dependent discharge voltage and current. Alternatively, one may chose to average over one pulse and use the duty cycle  $\delta = t_{on} / (t_{on} + t_{off}) = t_p f_p$  to obtain

$$\bar{P} = \delta \int_0^{t_p} I(t)V(t)dt, \quad (2)$$

where  $t_p$  is the duration of one pulse and  $f_p$  is the pulse repetition frequency. What we see from these equations is that voltage and current are *proportionally* used in the calculation of power. Therefore, any *increase* in operational voltage necessarily implies a *decrease* of the nominal (averaged) current in order to keep the same averaged power, even as the actual current during pulses is much higher than in the DC case. As pointed out by Emmerlich and co-workers [8], the deposition rates of DC and HIPIMS operation could only be the same if the sputtering yields were exactly proportional to the voltage, which determines the energy of ions causing the sputtering. In agreement with their arguments, we will see that, with exceptions we will discuss, the well established theory of sputtering necessitates a reduction of the deposition rate when going to HIPIMS operation. After some complicated looking math, a very simple approximate formula will emerge. Apart from this, it is clear that HIPIMS is has a strong component of self-sputtering, and therefore a fraction of the sputtered material returns to the target and is not available for deposition at the substrate. Overall, four effects will be discussed.

## 2.1 The yield effect

Most of the voltage between cathode (target) and anode drops in the thin cathode sheath above the target. Ions at the sheath edge are accelerated towards the target by the electric field. If we assume that the sheath is smaller than the mean free path between collisions, the ion energy  $E_i$  (in eV) corresponds to voltage the drop  $V_{sheath}$  (in V); the charge state number  $Q_i$  is a multiplier in the case we deal with multiply charged ions, that is,

$$E_i = Q_i e V_{sheath}, \quad (3)$$

where  $e$  is the elementary charge. For the sake of simplicity, we assume here that the sheath voltage is approximated by the total voltage between target and anode,

$$V_{sheath} \approx V. \quad (4)$$

This assumption will be dropped in the next section.

The deposition rate at the substrate is proportional to the sputtering yield at the target. Since more than one ion species are involved in the sputtering process (e.g. gas and metal ions), the rate is strictly speaking proportional to the sum over the contributions from all ion species of type  $i$ :

$$R_s = C \int \sum_i \gamma_i(E_i) \Phi_i dA, \quad (5)$$

where  $C$  is a geometry factor that could also include scattering of sputtered atoms by the process gas,  $\gamma_i(E_i)$  is the energy-depending sputter yield by ions of type  $i$  impacting the target, and  $\Phi_i$  is the flux of ions of type  $i$  arriving at the target; the integration is over the target area. The integration is over the target area  $A$ . The flux of ions of type  $i$  gives the ion current density

$$j_i = eQ_i\Phi_i \quad (6)$$

and, taking the yield of secondary ions,  $\gamma_{SE}$ , into account, the current density is

$$j = j_i + j_{SE} = [1 + \gamma_{SE}(Q_i, V)] j_i, \quad (7)$$

resulting in the discharge current

$$I(t) = \int j(t) dA. \quad (8)$$

Any increase in voltage would then lead to an increase in sputtering yield, as shown in Fig. 1. It is well known, and evident from Fig. 1, that the *yield scales with the ion energy in a less than proportional manner*. The yields can be calculated with the TRIM [9] or similar Monte Carlo Code. Table 1 shows that the result for each combination of ion type and target material can be fitted by a function

$$\gamma_i = a_i E_i^{b_i}. \quad (9)$$

A reasonable approximation is  $b_i = b = 1/2$  for all curves. If we denote the total flux of ions of type  $i$  to the target as

$$F_i = \int \Phi_i dA \quad (10)$$

and take into account (3) we can rewrite (5) as

$$R_s = C \sum_i a_i (eQ_i V)^b F_i, \quad (11)$$

and (6) can be rewritten as

$$I_i = eQ_i F_i, \quad (12)$$

leading to

$$R_s = C \sum_i a_i V^b (eQ_i)^{b-1} I_i. \quad (13)$$

We are not interested in the momentary rate but in the rate averaged over the deposition time  $t_D$ ,

$$\overline{R_s} = \int_0^{t_D} R_s dt / t_D. \quad (14)$$

We can write the ratio of the HIPIMS and DC rates as

$$\rho = \frac{\overline{R_s^{HIPIMS}}}{R_s^{DC}}. \quad (15)$$

To evaluate this expression we look at a very simple case, namely HIPIMS with very short pulses. In this case, the ion flux to the target is (still) dominated by gas ions, typically singly charged argon, and so we can greatly simplify the terms containing sums and charge states. For DC operation, the rate is simply

$$R_s^{DC} = DV_{DC}^b I_{i,DC} \quad (16)$$

where the new constant  $D$  contains all the previous constants,  $D = Cae^{b-1}$ . For HIPIMS operation, we know that we need a higher voltage to drive the high power discharge pulse. Some systems apply a constant voltage, and we can write

$$V_{HIPIMS} = KV_{DC} \quad (17)$$

with  $K > 1$ . The rate can then be written as

$$\begin{aligned} \overline{R_s^{HIPIMS}} &= \int_0^{t_D} Cae^{b-1} (KV_{DC})^b I_{i,HIPIMS}(t) dt / t_D \\ &= DK^b V_{DC}^b \int_0^{t_D} I_{i,HIPIMS}(t) dt / t_D \end{aligned} \quad (18)$$

For the evaluation of the integral we may utilize that the average HIPIMS power is equal to the DC power (that was the premise of comparing rates):

$$\overline{P_{DC}} = V_{DC} I_{i,DC} (1 + \gamma_{SE}) = \overline{P_{HIPIMS}} = KV_{DC} \int_0^{t_D} (1 + \gamma_{SE}) I_{i,HIPIMS} dt / t_D \quad (19)$$

Combining (15) to (19) we finally arrive at a very simple expression for the relative HIPIMS rate:

$$\rho = K^{b-1} \quad (20)$$

The constant  $K > 1$  describes how much the HIPIMS voltage is higher than the DC voltage. With  $b \approx 1/2$  we see that the more the HIPIMS voltage is enhanced compared to the DC voltage, the greater is the reduction of the HIPIMS deposition rate. This result is simply due to the fact that the sputtering yield does not scale linearly with the energy of ions.

It is interesting to note that all the specifics about the HIPIMS pulse have disappeared in (20). Of course, this is because we considered the simplest case but it is also an indication that the fundamentals of the yield effect do not depend on the details of the pulse: as long as sputtering occurs at higher voltage, the rate, normalized by average power, will go down.

To see how big the yield effect is, let us pick an example. DC sputtering of copper could be done with 350 V, and the HIPIMS pulse could be run with 700 V, a factor  $K = 2$  higher. Since  $b \approx 1/2$ , the relative rate is  $2^{-1/2} = 0.707$ , i.e. a reduction by about 30%.

## 2.2 The impedance effect

In the previous section, it was assumed that the sheath voltage can be estimated by the total voltage between target and anode, see equation (4). Of course, some portion of the voltage does not drop in the sheath but drops in the plasma. The total impedance of the discharge is composed of the sheath impedance and plasma impedance,

$$Z = Z_{sheath} + Z_{plasma} \quad (21)$$

and

$$V = V_{sheath} + V_{plasma} \quad (22)$$

The plasma impedance is due to the collisions of charged particles. The character of those collisions changes from collisions with gas atoms to collisions with charged particles as the degree of ionization increases and the plasma changes its composition. Furthermore, the presence of the magnetic field affects the impedance because the

transport of charged particle is governed by gyration (electron motion) and electron-ion coupling (ion motion).

Since sputtering is determined by the energy of ions impacting the target, we should write (13) accordingly:

$$R_s = C \sum_i a_i (V - V_{plasma})^b (eQ_i)^{b-1} I_i. \quad (23)$$

where  $V$  is voltage between target and anode and  $V_{plasma}$  is the portion of that voltage dropping in the plasma. Estimates show that the plasma conductivity in the HIPIMS case is higher than in the DC case, however, inductive components  $\sim dI/dt$  can reduce the voltage available for the sheath. As a consequence the sheath voltage may not be exactly the same fraction of the total voltage.

The sheath voltage determines the yield (equations (3) and (9)) whereas the total voltage is used to calculate the power used for normalization of the rate. Depending on the HIPIMS current pulse shape, balancing of the magnets, and type of plasma, the impedance effect may enhance or decrease the relative rate.

### 2.3 The species effect

From Figure 1 and Table 1 one can see that the sputter yield is largely determined by the target material (more precisely, by the surface binding energy) and to a lesser degree by the kind of ions that cause the sputtering. The curves for Ar→Cu and Cu→Cu, and for Ar→Ti and Ti→Ti, are close, respectively, but not identical. We can see a slight reduction, about 10% for the most relevant range of ion energy, when the sputtering switches from argon sputtering to self-sputtering. As self-sputtering becomes more prominent or even dominant, especially for long pulses, the rate for self-sputtering should be considered, and not the rate for argon sputtering, as done with conventional DC sputtering.

### 2.4 The return effect

A survey of experiments [7] found a reduction of HIPIMS deposition rates to about 20-40% compared to DC rates at the same average power. We recall that HIPIMS is based on ionization of the sputtered material and the onset of self-sputtering. The flux of sputtered material to the substrate is reduced by a factor  $(1-\alpha\beta)$ , where  $0 \leq \alpha \leq 1$  is the ionization probability and  $0 \leq \beta \leq 1$  is the probability that the newly formed ions return to the target. Therefore, equation (5) needs to be modified:

$$R_s = C (1 - \alpha\beta) \int \sum_i \gamma_i (E_i) \Phi_i dA. \quad (24)$$

As discussed in the literature [10], self-sputtering can dominate the process, and in fact sputtering runaway occurs when the condition

$$\alpha\beta\gamma_i > 1 \quad (25)$$

is fulfilled. The runaway will be limited by either constraints of the power supply or by the establishment of a new dampening mechanism, which can put the HIPIMS system into a new equilibrium that is within the available power. Fig. 2 illustrates that for copper. It is very likely that the damping mechanism is associated with the large flux of neutrals, which lead to charge exchange collisions and prevent the build-up of a high concentration of multiply charged ions. Those multiply charged are important for the maintenance of the discharge because singly charged metal ions have only a very small

secondary electron yield [11, 12]. In any case, the product  $\alpha\beta$  can readily reach values of 0.5, for example, and therefore the overall rate would be reduced to less than 50%.

### 3. The Technologist/business view

The underlying concern with reduced deposition rates is lost productivity and profitability. One approach is to simply operate the sputtering equipment at higher average power provided the cooling limitations allow this to happen. The additional costs related to greater energy consumption are only a minor factor in the bigger picture of equipment and other operational costs. Should higher average power not be possible, the question is really: Do the advantages of HIPIMS justify the reduced productivity? With HIPIMS, we have new opportunities to produce films that are denser than normally sputtered films, and in many cases film properties like phase and preferred crystalline orientation can be tuned. If this is of no importance, HIPIMS may not be the right choice. The higher value added by advanced processing is the key premise of HIPIMS, and the lower rates, compared to DC at the same average power, is a technology property. In the same sense, we could compare e-beam evaporation and magnetron sputtering to conclude that sputtering would be in most cases inferior because the rates are lower. Clearly, we would dismiss this conclusion because it does not take into account the properties of sputtered films compared to e-beam evaporated films.

### 4. Temperature dependent sputter yields

It should be mentioned that the HIPIMS rates may be enhanced, and may even exceed typical DC rates, if new effects come into play. Most notably, the surface of the target, and especially the race track zone, may be heated to such degree that the target material approaches the melting point and evaporation sets in. Of course, melting is not desired, and we also have to worry about overheating the magnets on the backside of the target.

Chistyakov [13, 14] demonstrated a HIPIMS version with modulated power that utilizes the effect of high target temperature. By stepwise increasing power within 1-2 ms, high rates were obtained for Al<sub>2</sub>O<sub>3</sub>, TiN, and other materials.

There is some confusion in the literature whether or not the sputtering yield is temperature dependent, i.e., whether rate enhancement effects are due to enhanced sputtering or evaporation. Vaulin and co-workers [15] found an increase in the yield for copper when the temperature of the target exceeded about 800°C; this work was cited by Fortov [16] (p. 119). Bohdanský and coworkers [17] showed that this increase is related to evaporation rather than sputtering. Behrisch and Eckstein [18, 19] generally agree but acknowledged that the surface binding energy has a nonlinear effect on the yield. The surface binding energy can be derived from the heat of sublimation *at a given temperature*. Even as the heat of sublimation decreases with temperature, evaporation is overtaking the loss rate at high temperature [18] by a wide margin and we conclude that evaporation is the relevant mechanism. The vapor pressure of the different materials [20] is of course the right gauge for estimating the relevance of evaporation.

### 5. Summary and Conclusions

The physics of sputter processes suggests that a rate reduction should be expected when the mode of operation is switched from DC to HIPIMS. In this comparison, the

time-averaged power was used for normalization, which is arbitrary from a physics point of view but reasonable from an application / business point view. Four different effects have been considered to explain the differences seen between DC and HIPIMS rates. Higher rates are possible under special circumstances such as very high target temperature.

It is argued that the value added, especially the higher film quality, should be taken into account when making a decision to utilize HIPIMS. Although HIPIMS is not likely to replace conventional sputtering due to somewhat higher equipment costs and reduced rates (given the questionable normalization), it will find an important place among PVD technologies for those application that require high film density films and superior quality.

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**Table 1:** Fits of sputter yields assuming a  $\gamma_i = aE_i^b$  dependence;  $a$  and  $b$  are the fit parameters,  $R$  is the correlation coefficient.

	$a$	$b$	$R^2$
Ar→Cu	0.1421	0.468	0.980
Cu→Cu	0.0691	0.556	0.985
Ar→Ti	0.0425	0.443	0.977
Ti→Ti	0.0285	0.484	0.978

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## Figure Captions

Fig. 1 Sputtering yields for copper and titanium as a function of ion energy, as calculated by the TRIM2006 code.

Fig. 2 Current-voltage-time characteristics for HIPIMS discharges with copper target and argon at 1.8 Pa. The labels indicate that metal self-sputtering runaway occurred first at a HIPIMS voltage of 535 V, finding a new equilibrium as evident by the steady current level. At higher voltage, the equilibrium is at a higher level.

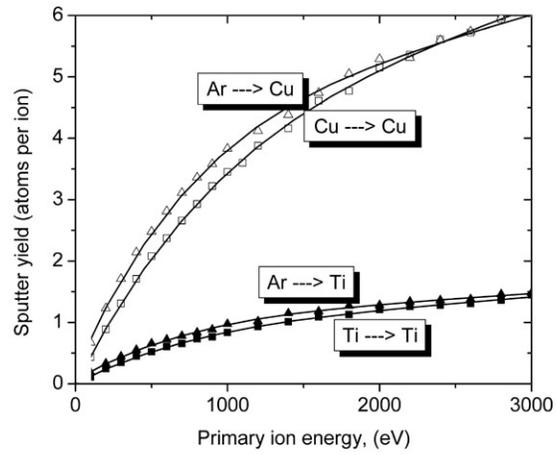


Fig. 1

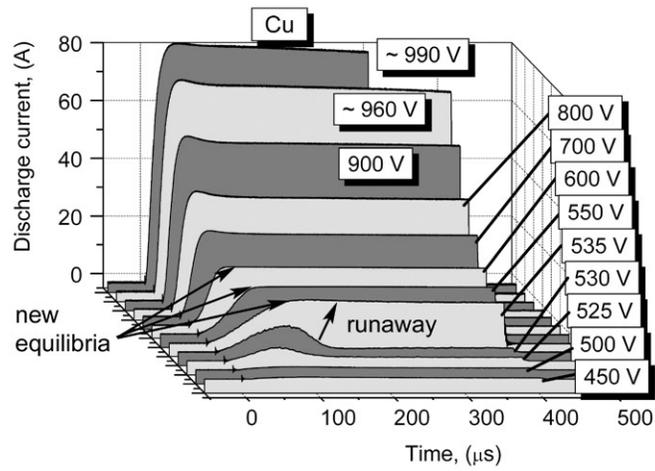


Fig. 2