UMONS
Université de Mons

Quelle alimentation pour quel plasma ?

Pulvérisation cathodique en régime d'impulsion de haute puissance (HiPIMS)

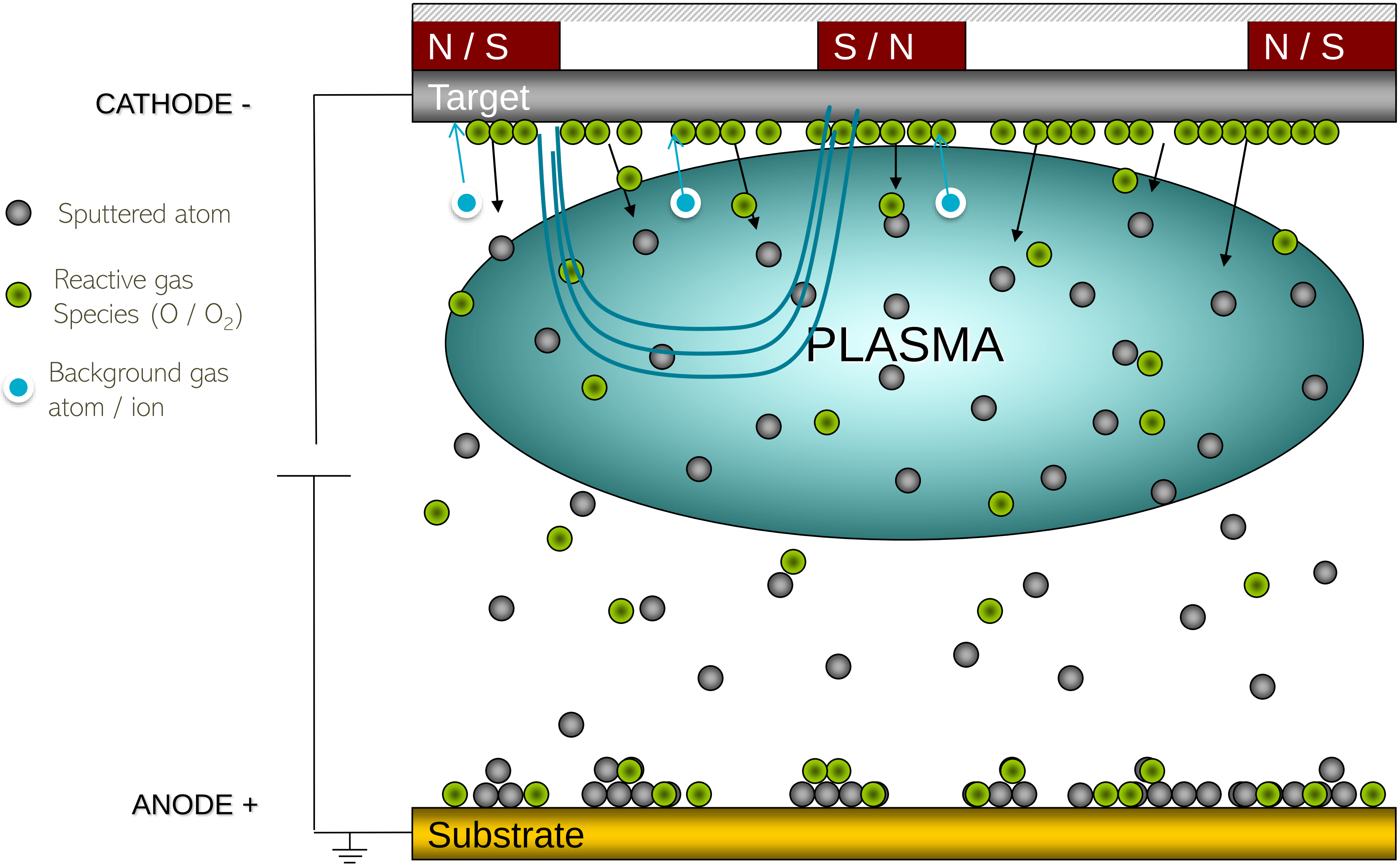
CHIPS
Chimie des Interactions Plasma Surfaces

stephanos.konstantinidis@umons.ac.be

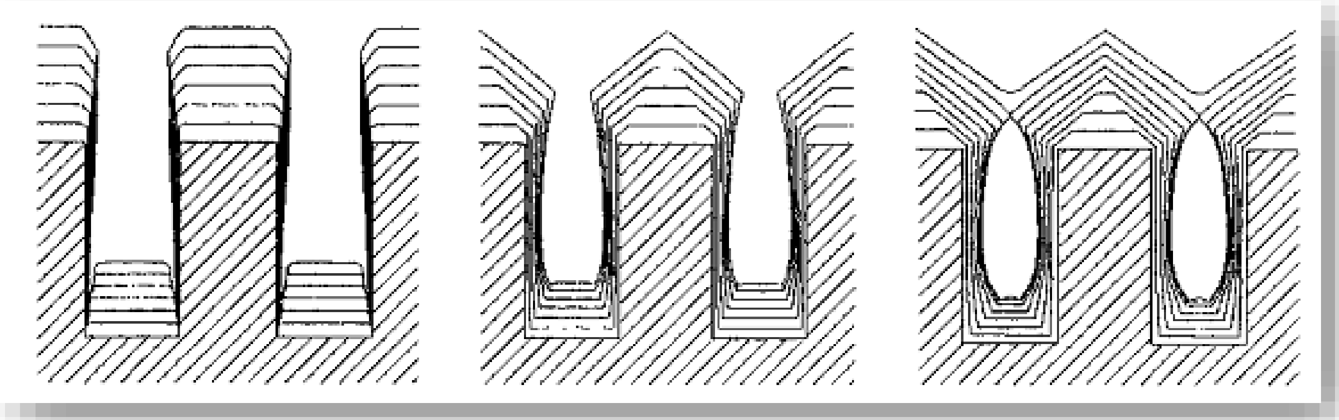
Orléans, 3/4/2019

Table des matières

La pulvérisation cathodique magnétron pour le dépôt de couches minces



Pulvérisation en régime DC



S. Hamaguchi and S. M. Rossnagel, J. Vac. Sci. Technol. 1996.

…problème !

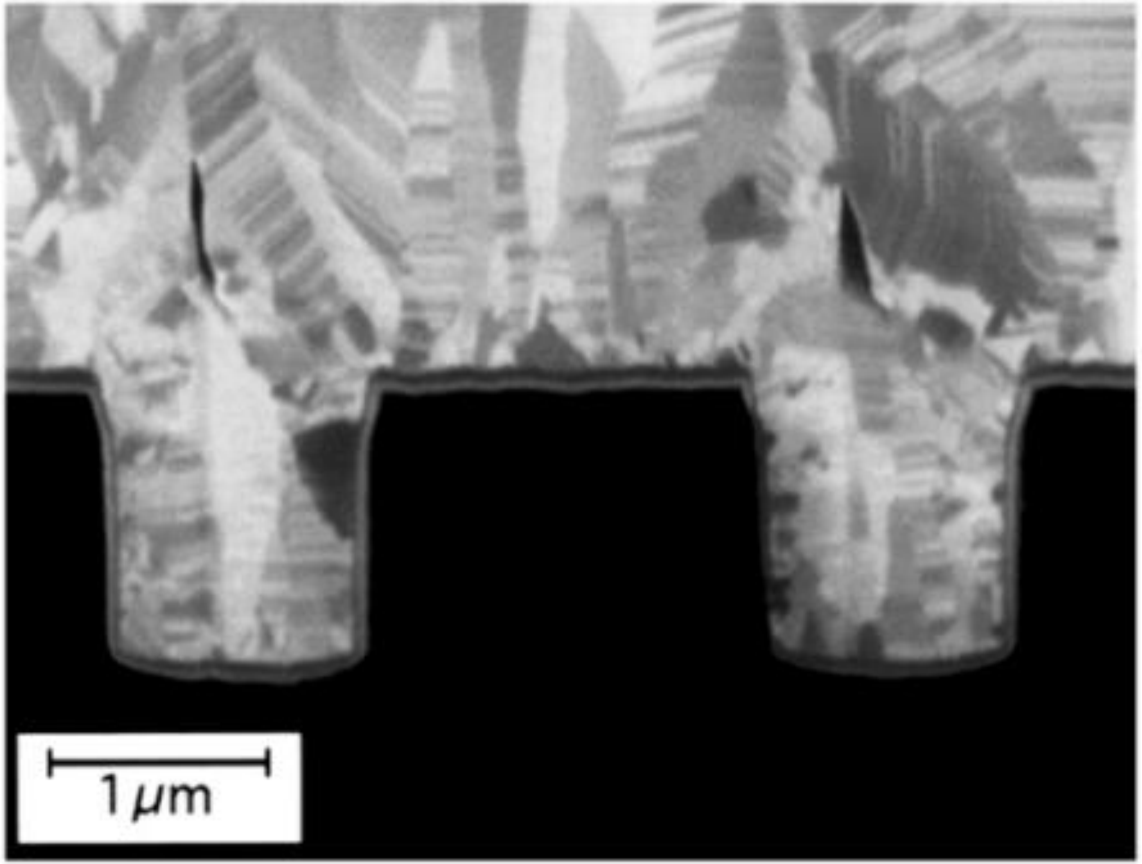
La solution :
Ioniser les atomes métalliques

Pourquoi l’HiPIMS ?

⇒ Augmenter **l’ionisation** de la vapeur métallique

1. Via la polarisation du substrat : contrôler **l’énergie cinétique** des espèces qui participent à la croissance du film
    - Cristallinité, micro/nanostructure, rugosité,… sont modifiés
2. Contrôler la **trajectoire** des espèces qui participent à la croissance du film
    - Dépôt conforme

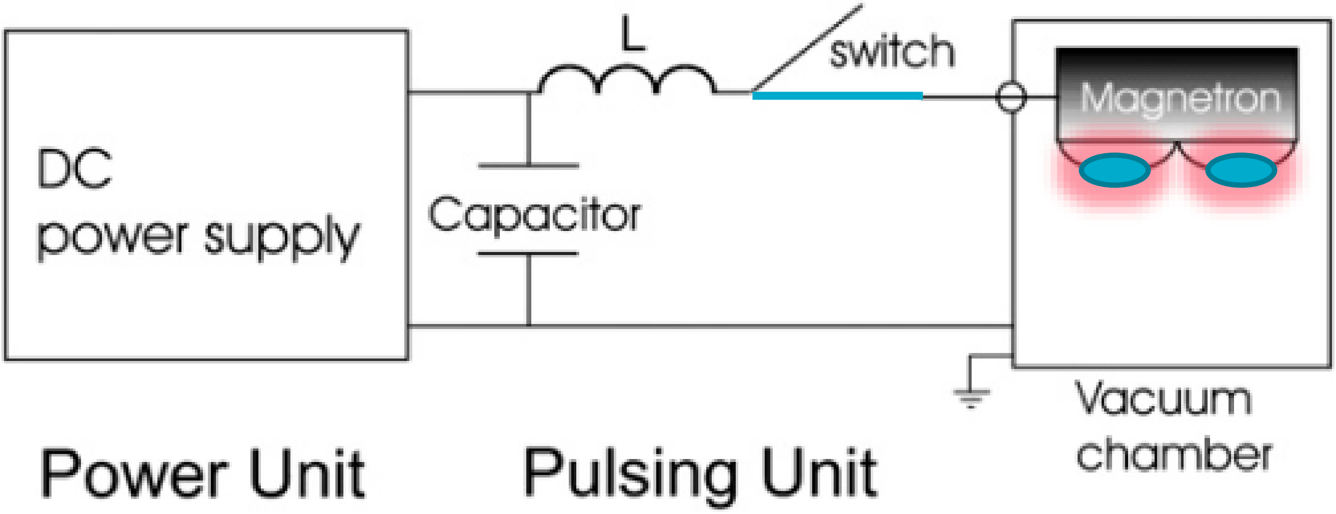
Sarakinos, Alami, Konstantinidis, Surf. Coat. Technol 2010



Kouznetsov et al, Surf. Coat. Technol. 1999

Comment faire ?

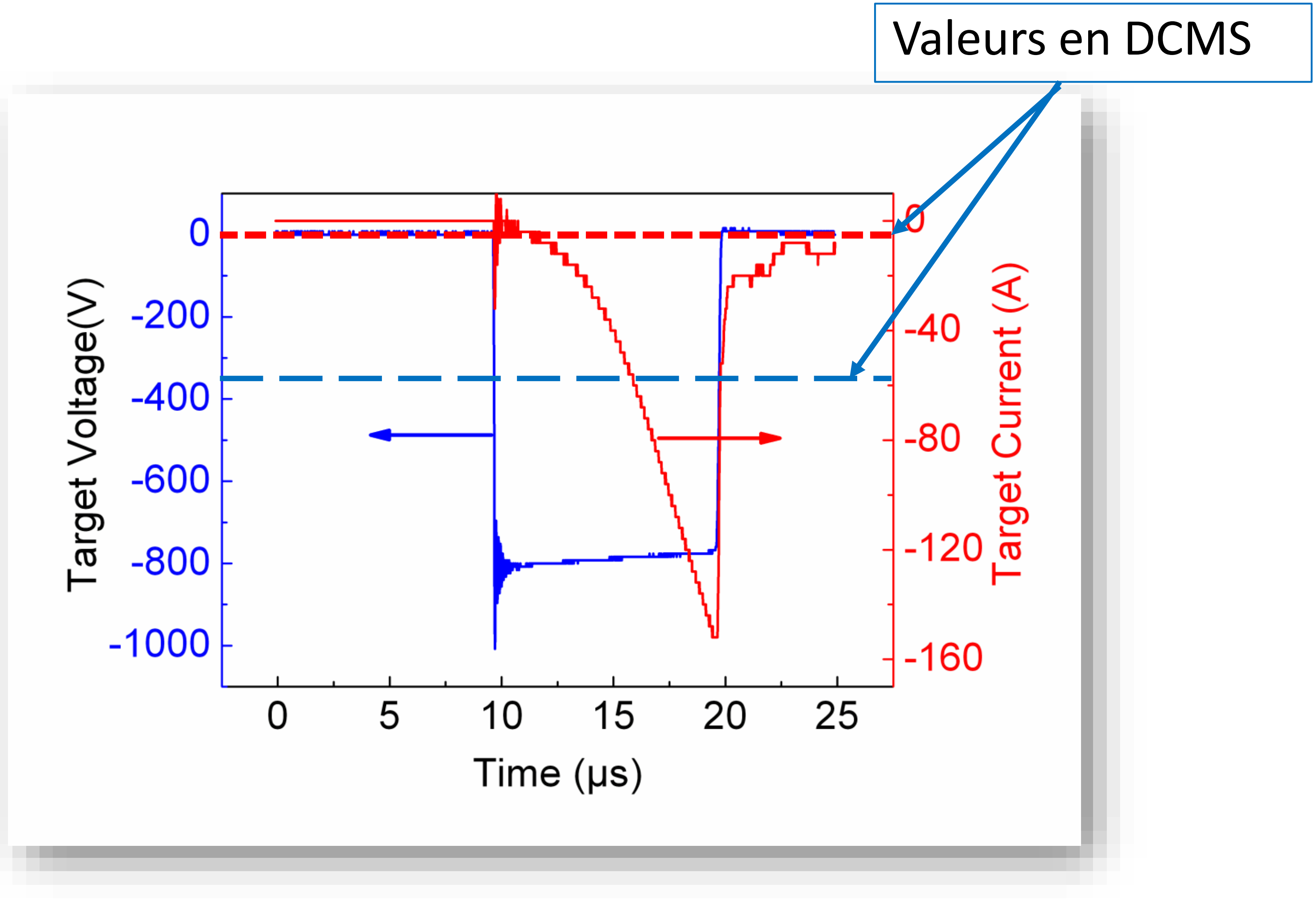
Architecture d’une alim HiPIMS



Alimentation capable de délivrer

- Tension de 1 – 2 kV
- Courant pic de plusieurs 10-100aines d’A

Courbes I-V(t) typiques

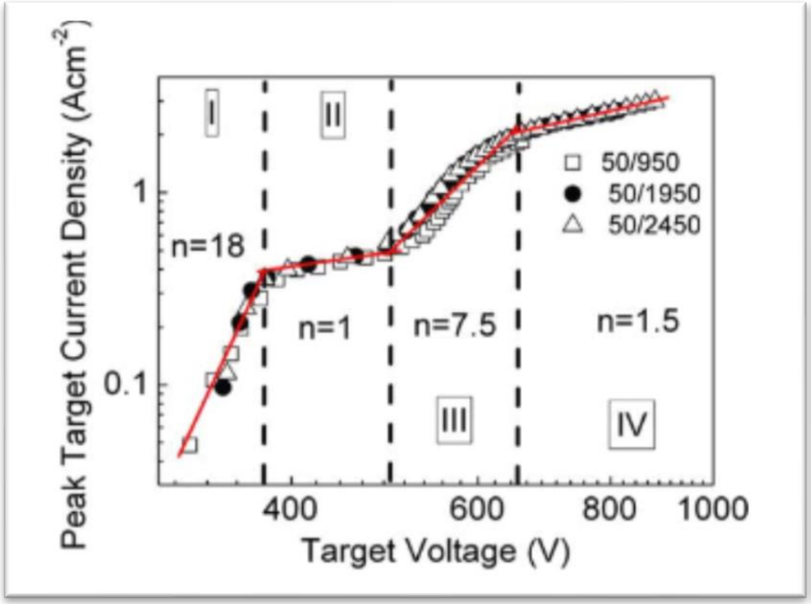

Valeurs en DCMS

Vers une définition de l'HiPIMS

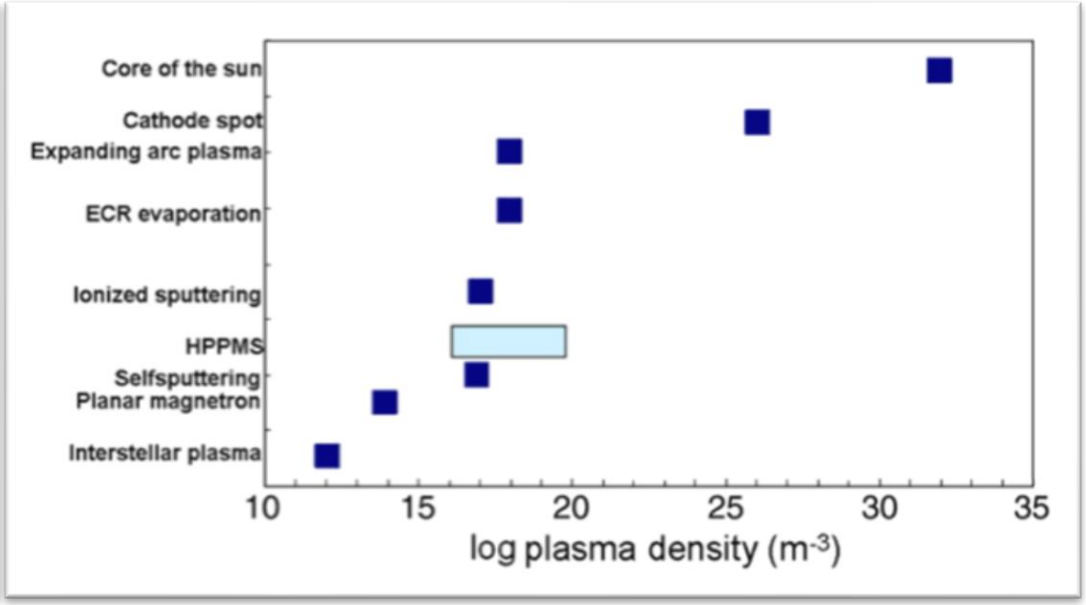
1. Impulsions électriques
   1. Duty cycle ≤ 1%
2. Cathode magnétron
   1. Décharge dans champs ExB
3. Haute puissance/courant crête
   1. ~kW ou A cm^{-2}
   2. ⇒ $N_e \sim 10^{12-13}$ cm^{-3}
4. Ionisation importante du matériau à déposer

Sarakinos, Alami, Konstantinidis, Surf. Coat. Technol, 2010.

L’HiPIMS et
les autres technique PVD



Alami et al, Appl. Phys. Lett. 2006



Alami. PhD Thesis, Linköping University, 2005.

Plusieurs approches de l’HiPIMS

- Différentes durées d’impulsion
- Variation & Options ajoutées

Différentes approches de l’HiPIMS

1. « Classique » (50 – 200µs)
2. Impulsions courtes (1 – 20µs)
3. Impulsions longues (200 – 400µs)
4. Impulsions XL (400 – 4000µs)

« Classic » HiPIMS (50 – 200µs)

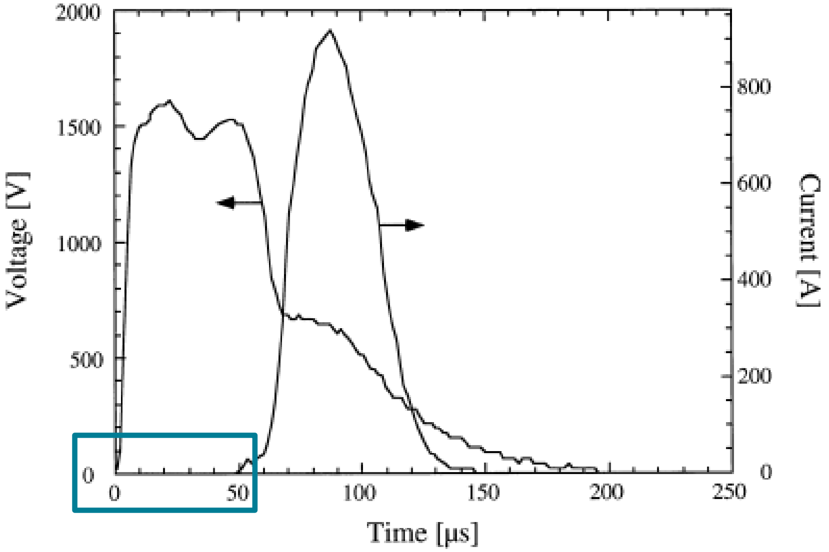
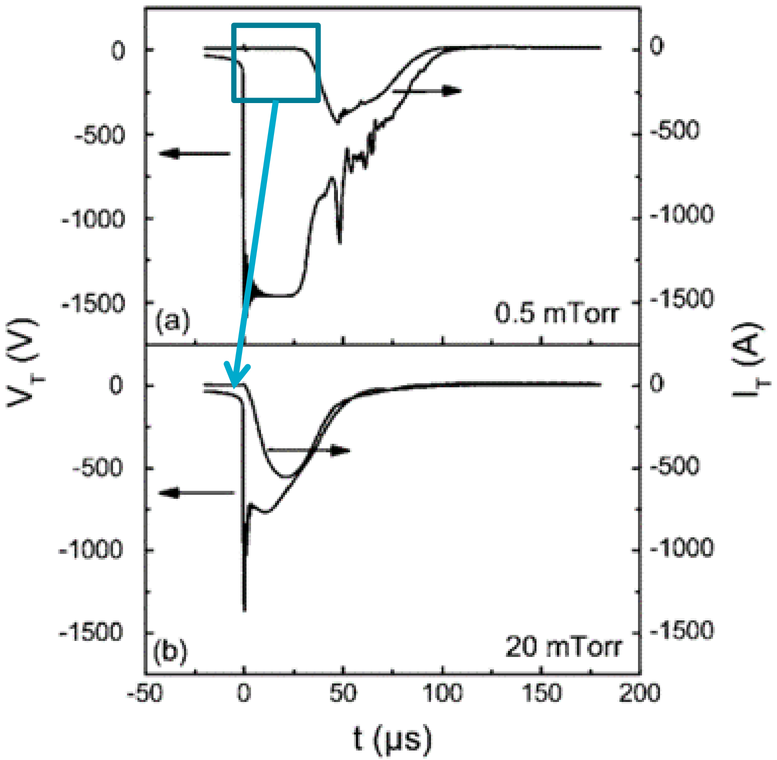
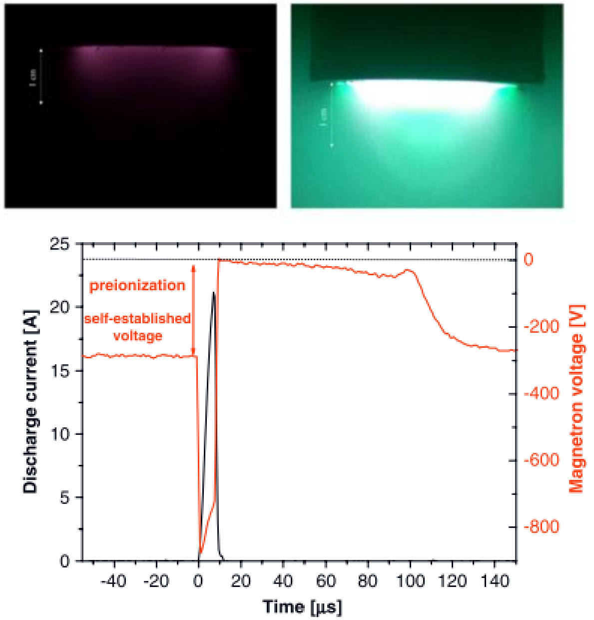


Fig. 1. A typical voltage and current time trace for the high power pulsed discharge. A Cu cathode was used and the sputtering gas, Ar, was maintained at 0.065 Pa (0.5 mTorr). The maximum error in the time adjustment between the two traces are estimated to 10 µs.



[1] Kouznetsov, Macak, Schneider, Helmersson, Petrov, Surf. Coat. Technol. 1999
[2] Konstantinidis, Thesis, 2004
[3] Alami, Gudmundsson, Bohlmark, Birch, Plasma Sources Sci. Technol. 2005

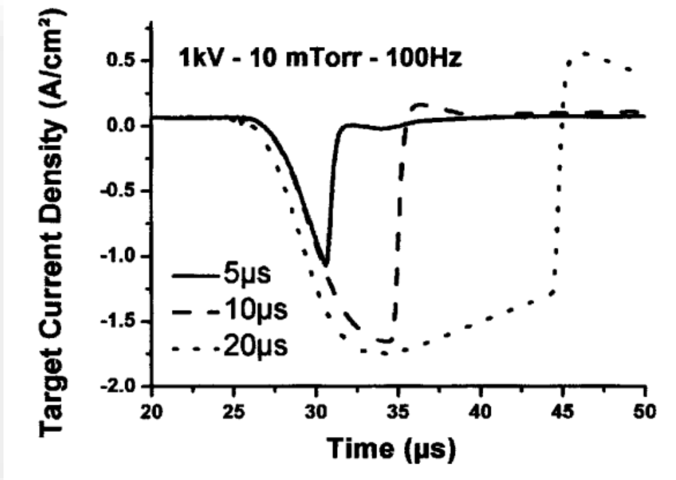
Impulsions courtes (1 – 20µs)



Vasina, et al, Plasma Sour. Sci. Technol. 2007.

Préionisation du gaz [1, 2]

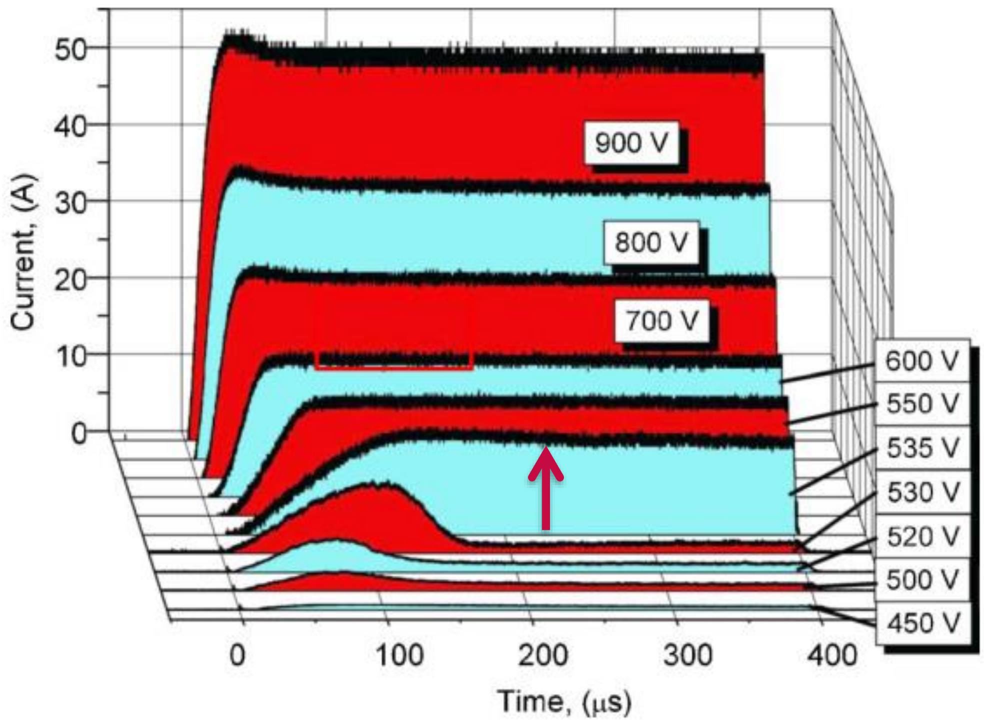
- Tension DC (qques mA)
- Plasma secondaire RF ou µW
- Accroitre la fréq de répétition des impulsions (>500Hz)



Konstantinidis et al, J. Appl. Phys. 2006

[1] Ganciu, Konstantinidis, et al, J. Opt. Adv. Mat. 2005.
[2] Konstantinidis, PhD Thesis, 2004

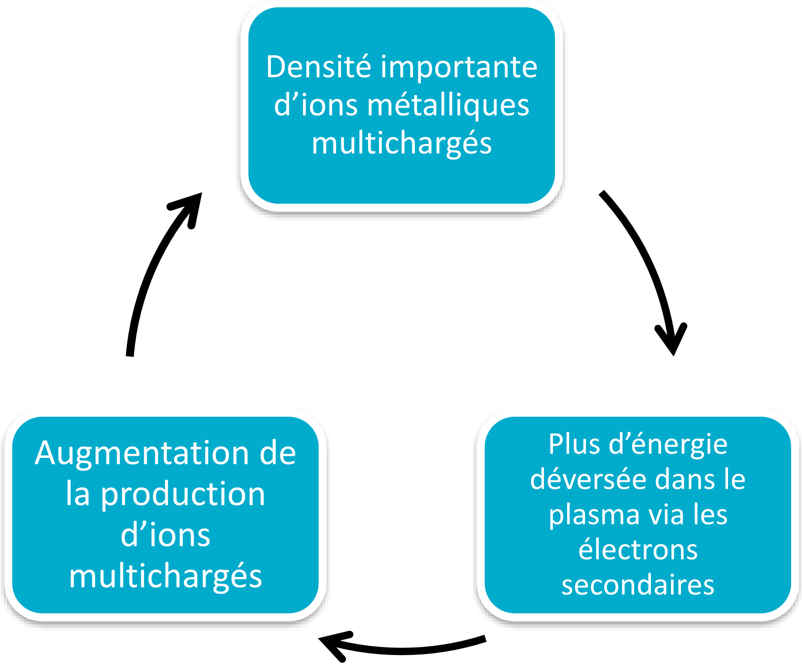
Impulsions longues (200 – 400µs)



Anders, Andersson, Ehiasarian, J. Appl. Phys. 2007

Self-sputtering runnaway

- Possible si $\alpha\beta\gamma_{ss}>1$
  - α probabilitié qu’un atoms pulvérisé soit ionisé,
  - β probabilité que l’ion métallique retourne à la cible
  - γ_{ss} est le rendement d’auto pulvé
    - Haute puissance + long pulses pour atteindre ce régime
- Ions métalliques multichargés sont importants
  - Augmentation de l’émission d’électrons secondaires (émission cinétique)



Densité importante d’ions métalliques multichargés

Plus d’énergie déversée dans le plasma via les électrons secondaires

Augmentation de la production d’ions multichargés

Anders, Appl. Phys. Lett. 2008

Pulses X-Large (400 – 4000µs)

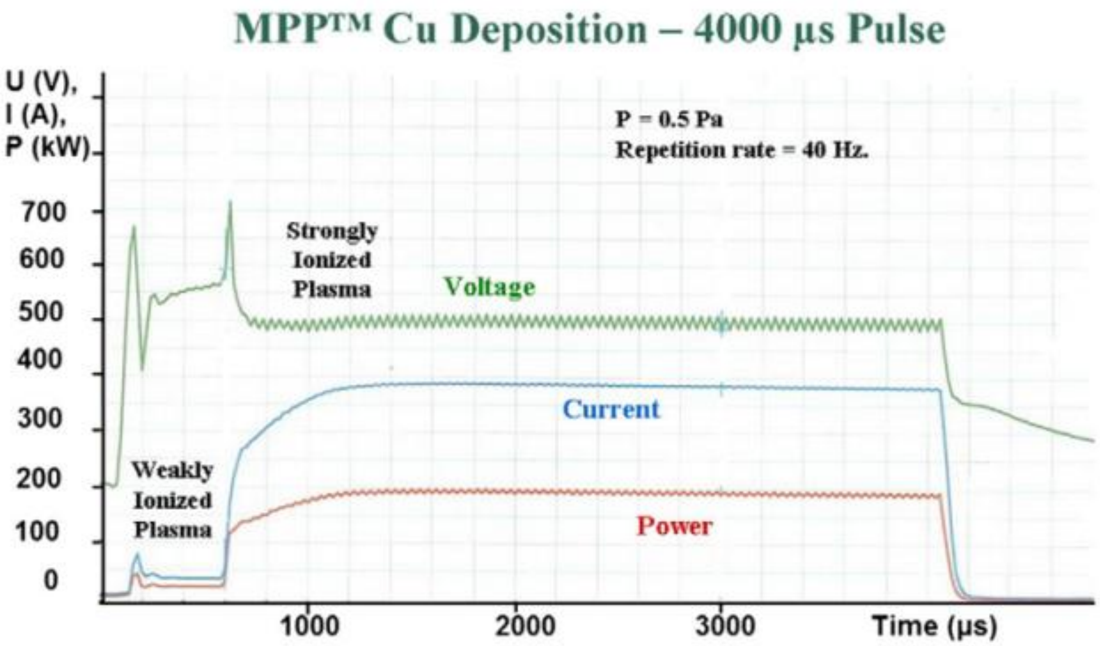


Fig. 8. Target voltage and current waveforms during the long-pulse operation. In the first 500 µs a weakly ionized plasma is generated which is followed by a highly ionized steady-state plasma (reprinted from [54] after permission, Society of Vacuum Coaters © 2007).

Chistyakov, Abraham, Sproul, Moore, Lin, SVC 2007.

Variations :

1. HiPIMS avec DC superposé

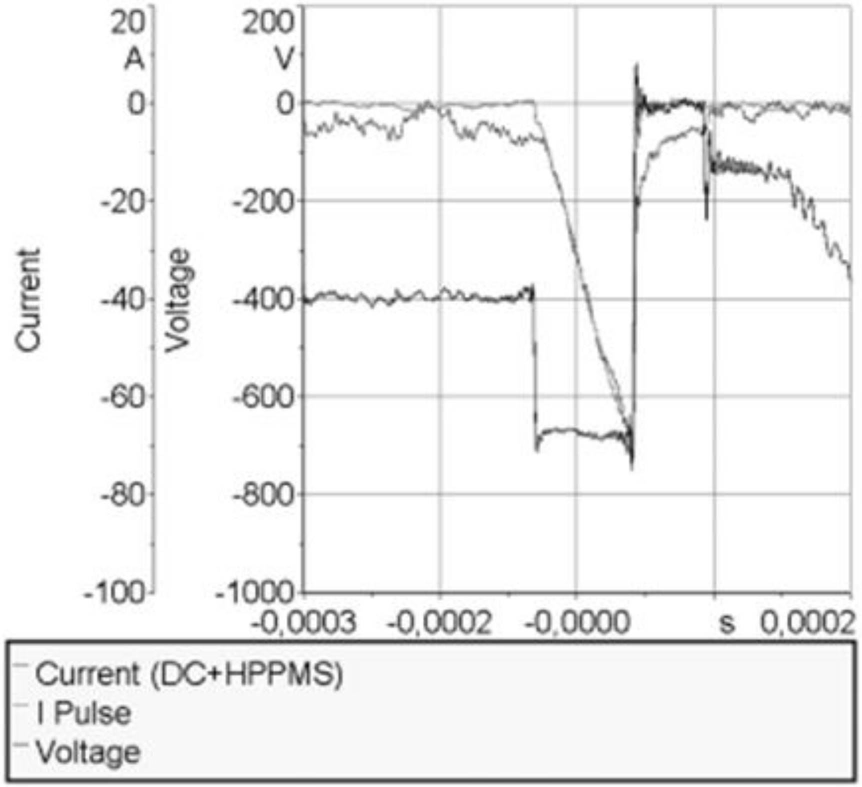
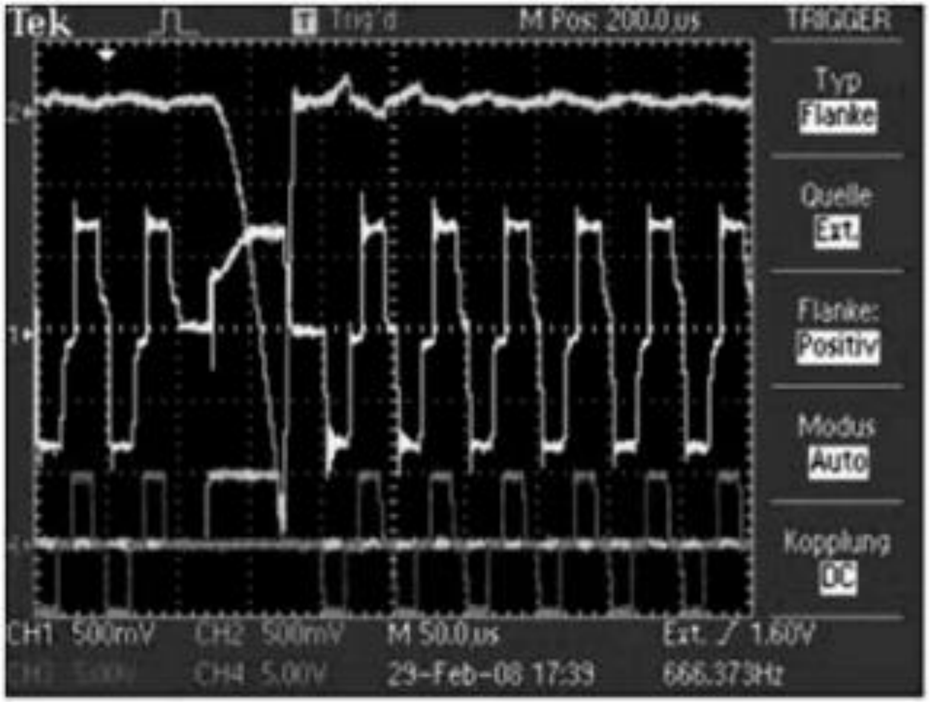


Figure 4: HPPMS for titanium sputtering; t_{on}: 90µs, t_{off}: 2190µs, U_{HPPMS}: 680V, 1kW supplying the pulse unit, 1.0kW dc power superimposed, UDC: 390V.

Bandorf, Falkenau, Schmidt, Mark, SVC 2007.

Variations :

2. HiPIMS avec MF superposé



Typ: Flanke

Quelle: Ext.

Flanke: Positiv

Modus: Auto

Kopplung: DC

CH1 500mV CH2 500mV M 50.0µs Ext. ∕ 1.60V

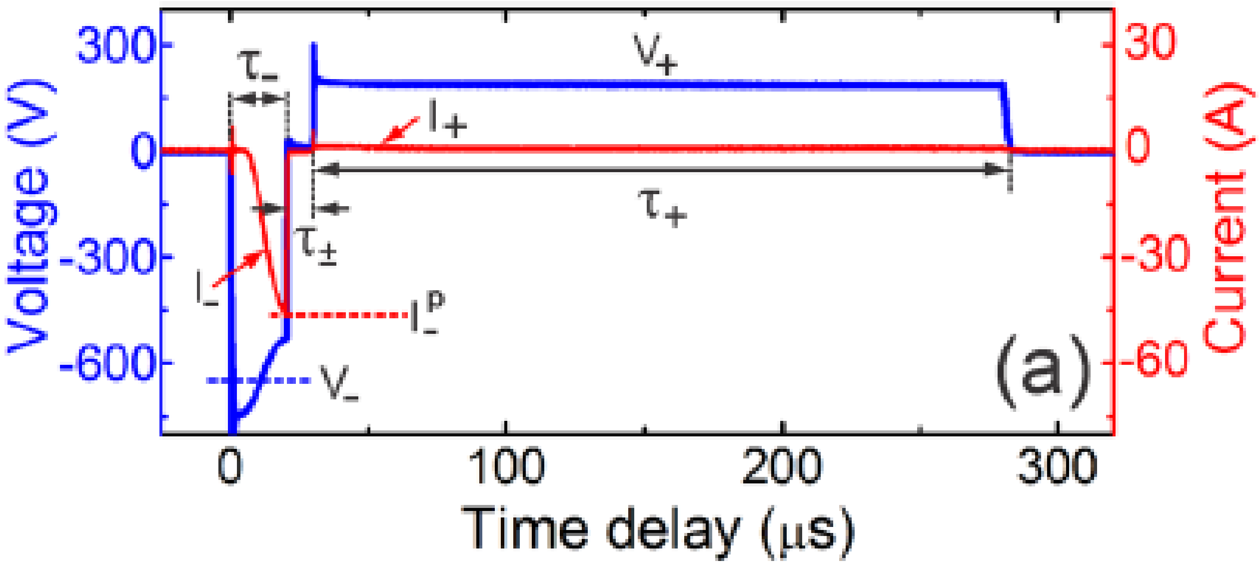
CH3 5.00V CH4 5.00V 29-Feb-08 17:39 666.373Hz

Figure 5: Screenshot of the pulse forms. Top: target current 300A; mid: target voltage 375V; bottom: control pulses. The length and the frequency of the HiPIMS pulse was 50µsec and 666Hz, respectively, the MF-frequency was 20.0 kHz.

Vergöhl, Werner, Bruns, Wallendorf, Mark, SVC 2008.

Variations:

3. HiPIMS bipolaire



Britun, Michiels, Godfroid, Snyders, Appl. Phys. Lett. (2018).

Options:
Suppresseur d'arcs

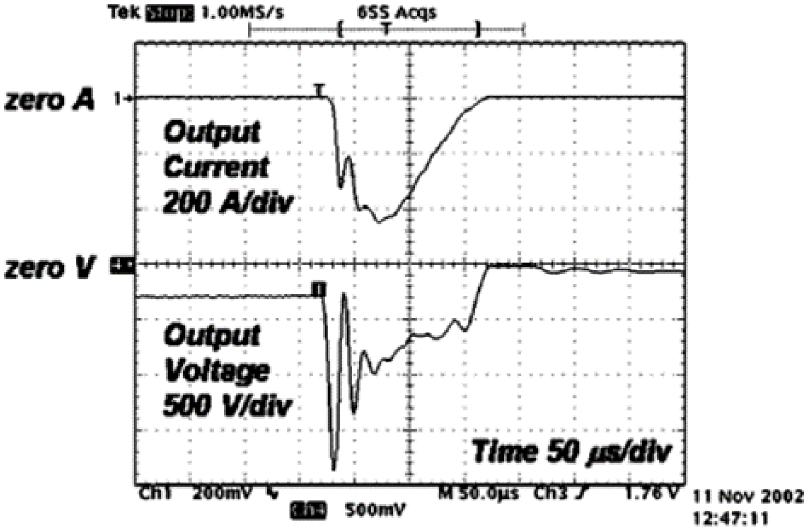
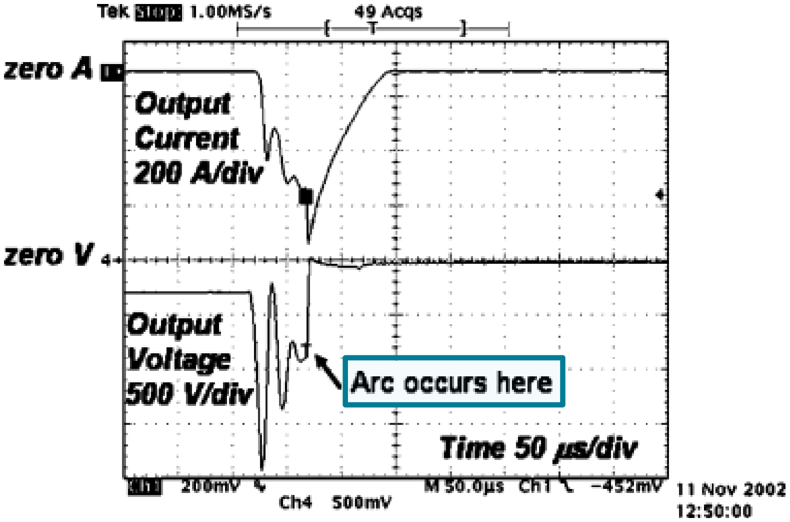


FIG. 5. Oscilloscope photo of normal operation into small magnetron.



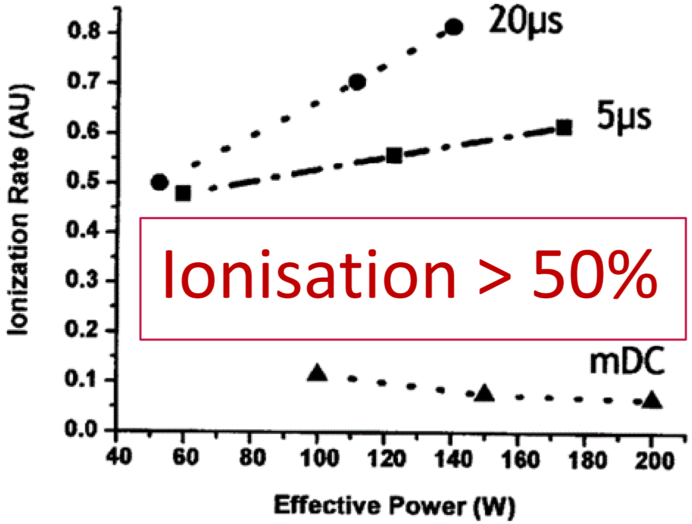
Arc occurs here

FIG. 6. Oscilloscope photo of arc handling into small magnetron.

Christie, Tomasel, Sproul, Carter, J. Vac. Sci. Technol. 2004.

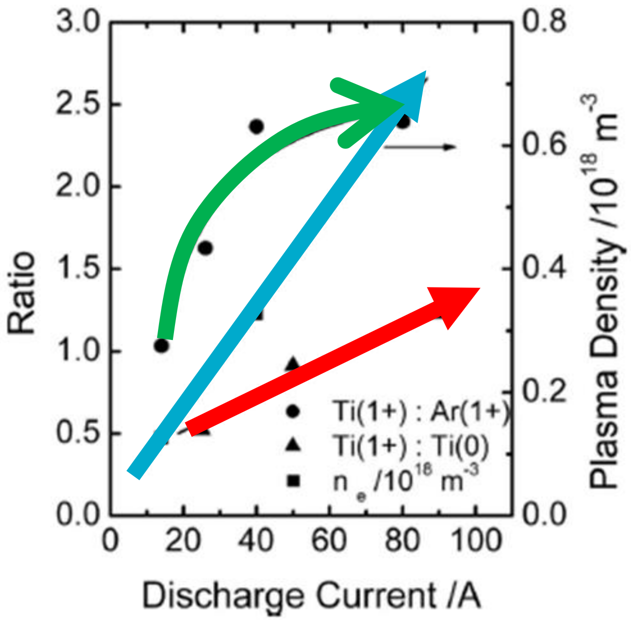
Taux d'ionisation

Ionisation = fct I_d et P_d
Plasma « métallique »



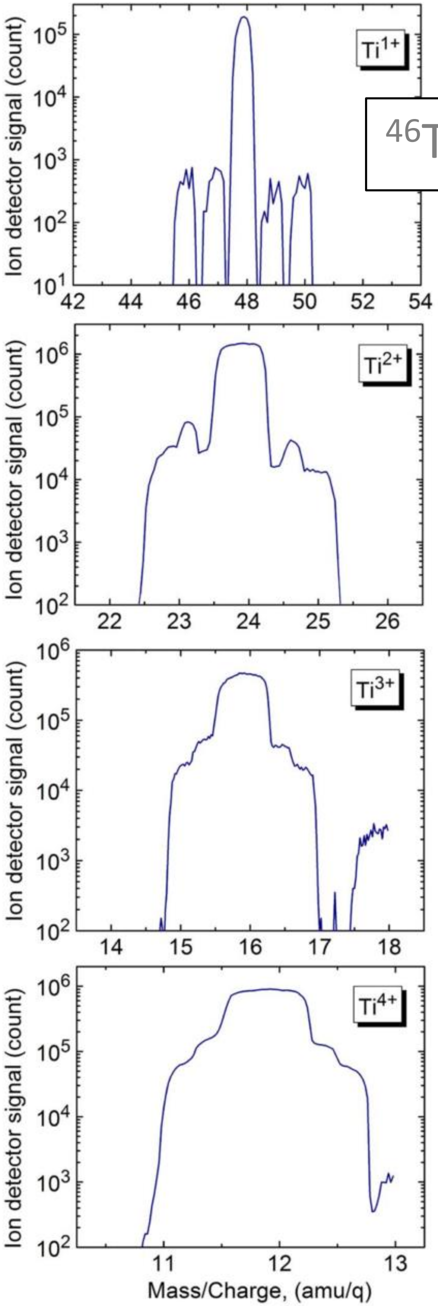
Ionisation > 50%

Konstantinidis et al, J. Appl. Phys.2006



Ehiasarian, Konstantinidis et al, J. Appl. Phys.2008

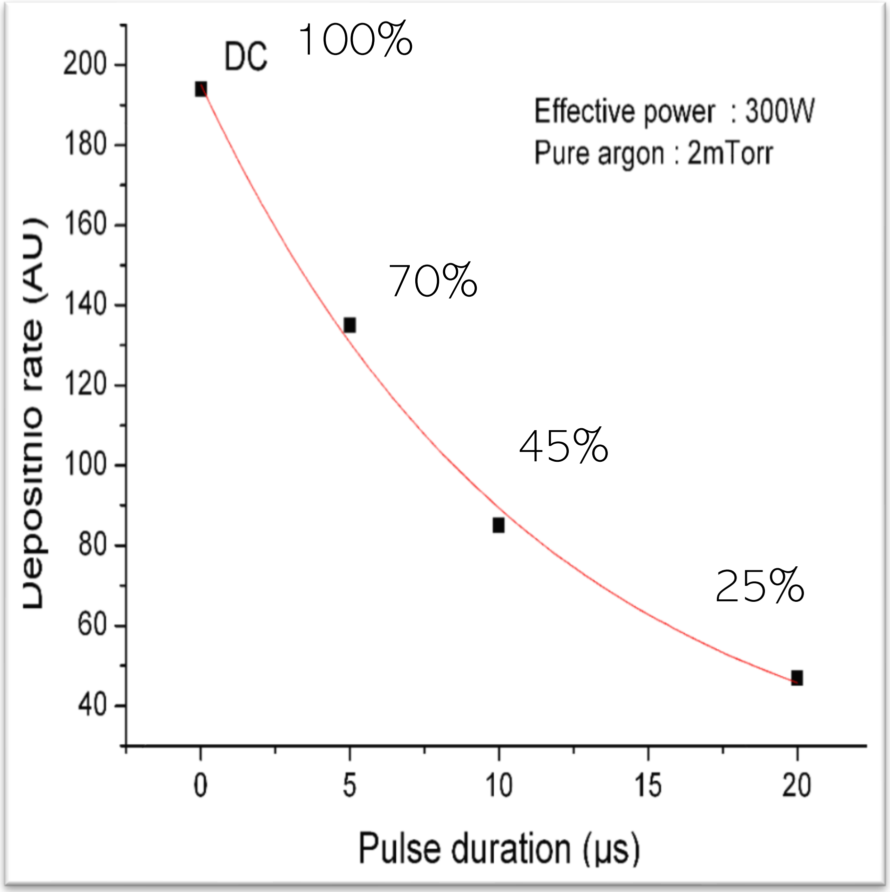
Production d’atomes multiplement ionisés



^{46}Ti , ^{47}Ti , ^{48}Ti , ^{49}Ti , ^{50}Ti

Andersson et al. Appl. Phys. Lett. 2008

Vitesse de dépôt en fonction de la puissance appliquée (ou du taux d'ionisation)



S. Konstantinidis et al, J. Appl. Phys. (2006).

Décroissance de la vitesse de dépôt

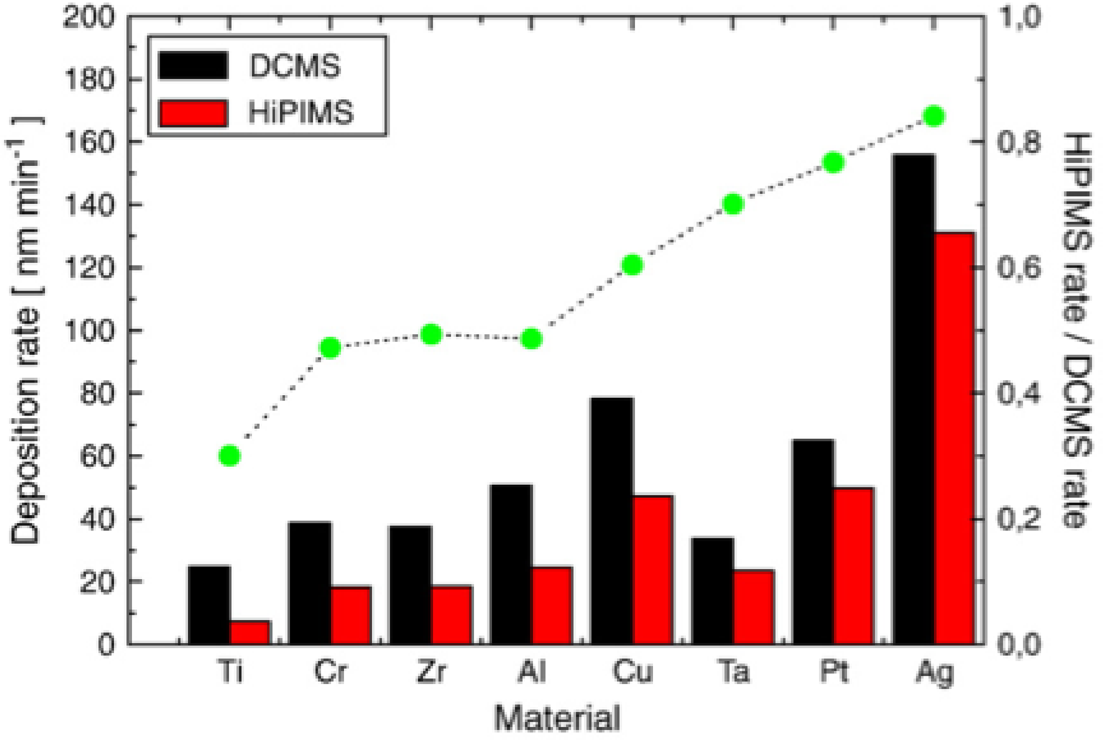


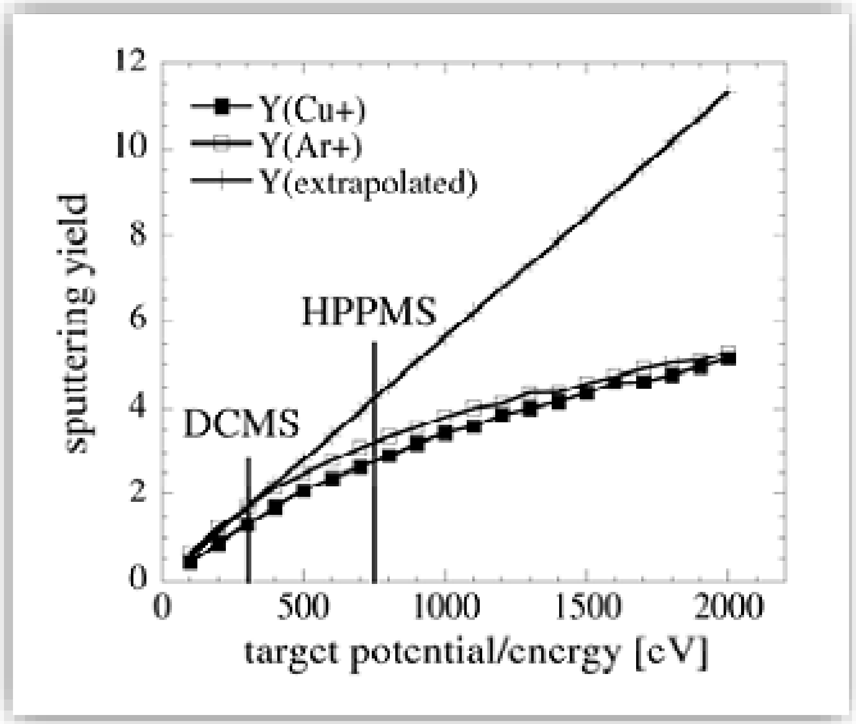
Fig. 1. The deposition rates for DCMS and HiPIMS discharges plotted as bars for the different target materials used (left axis). The deposition rate of HiPIMS over DCMS deposition rate is shown as a scatter plot (right axis).

Samuelsson et al, Surf. Coatings Technol. (2010).

…problème !

Plusieurs causes…

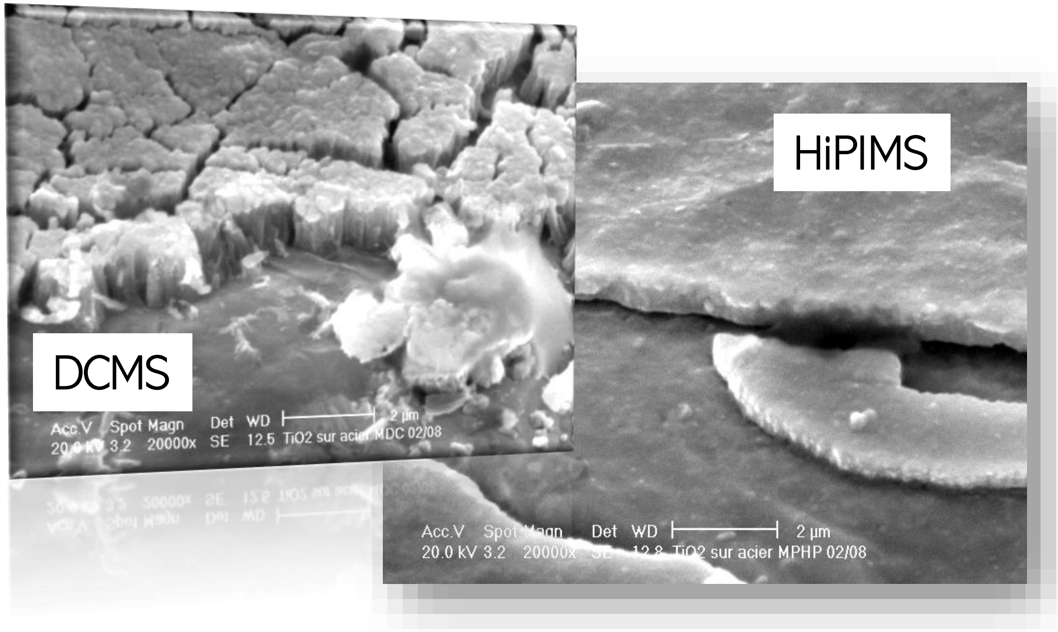
- Rendement de pulvé n'est pas une **fonction linéaire** de la tension cathodique [1]
- **Eventuelle perte de puissance** dans l'étage d'impulsion
- Transport des espèces vers le substrat : importance du champ B [2 - 6]



1) Emmerlich, Vacuum, 2008
2) Konstantinidis, Appl. Phys. Lett. 2006
3) De Poucques, Plasma Process. Polym., 2007
4) Lundin, Plasma Sources Sci. Technol., 2008
5) Bohlmark, Thin Solid Films, 2006
6) Mishra, Plasma Sources Sci. Technol., 2010

Comment mesure-t-on la vitesse de dépôt ?

- Augmentation de la **densité** des films alors qu'on mesure une épaisseur par profilométrie[1, 2]
- Plasma métallique propice à l'**auto-pulvérisation**[3-5]



1) Konstantinidis, Thin Solid Films, 2006
2) Konstantinidis, J.Vac. Sci. technol. B, 2007
3) Konstantinidis, J. Appl. Phys., 2006
4) Sarakinos, J. Phys. D., 2008.
5) Alami, Appl. Phys. Lett., 2006

Régime d'auto-pulvérisation

Courant d'ions Ar$^+$ à la cathode

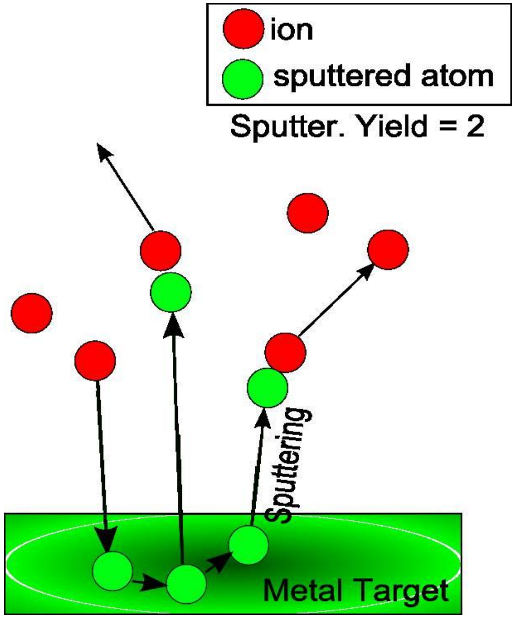
Rendement de pulvérisation
suite à l'interaction de Ar$^+$ avec la cathode

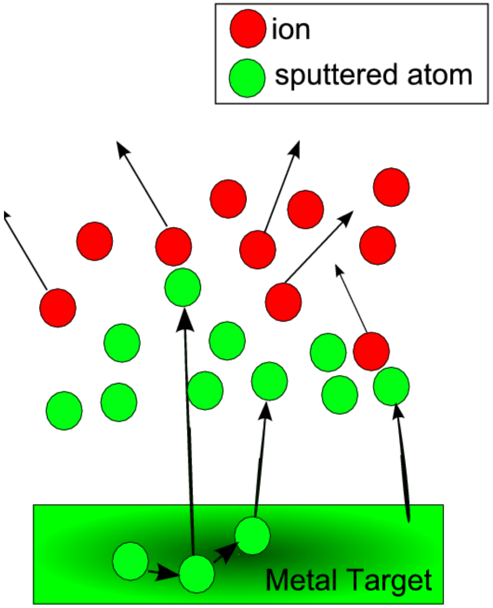
$$Q \propto \int_{time} \left[\underbrace{I_{G^+} \times Y_{(M-G^+)}}_{\text{Ar+ sputtering}} + \underbrace{I_{M^+}\left(Y_{(M-M^+)} \boxed{-1}\right)}_{\text{M+ sputtering}} \right] dt$$

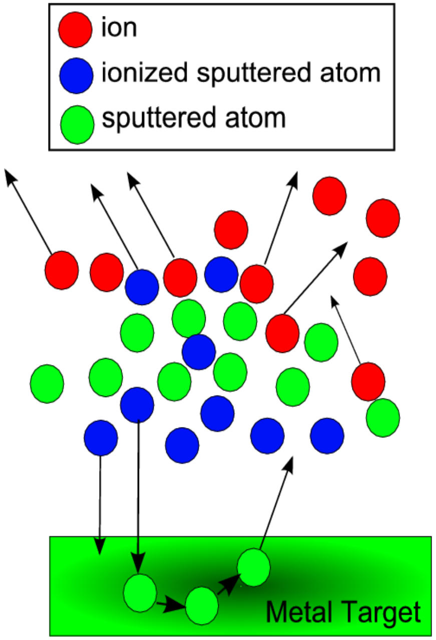
Taux de dépôt

Implantation de l'ion métallique dans cible :
Ne participe plus au dépôt

Le rôle du vent de pulvérisation



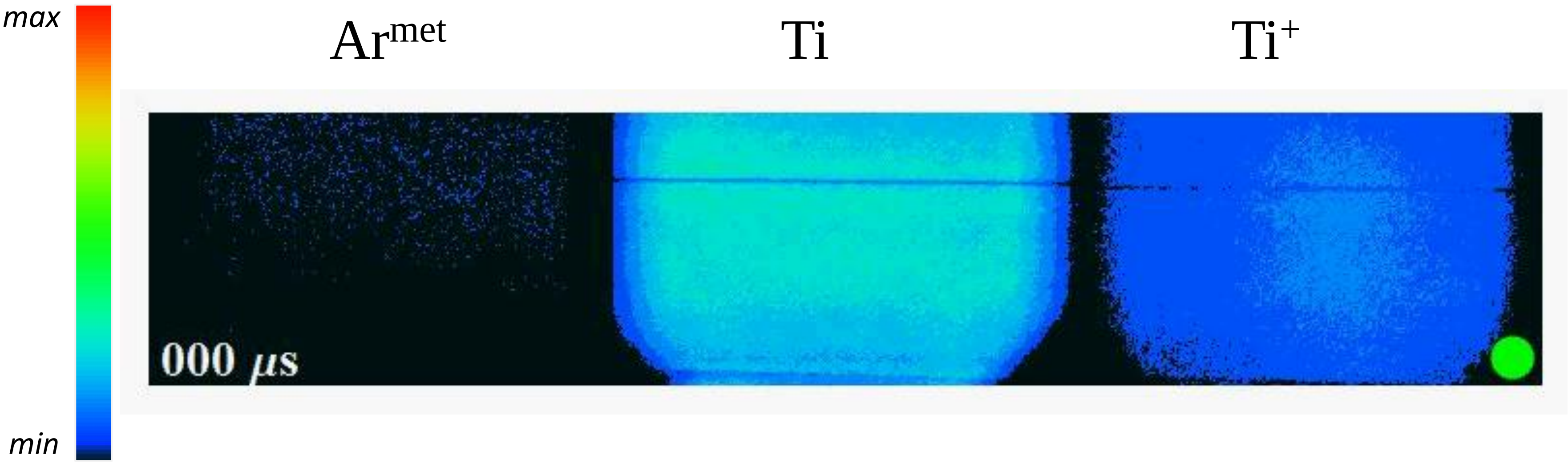




Hoffman, JVST A, 1985

Mise en evidence de la raréfaction

Pulse - 20 µs
Period - 1 ms
Pressure - 20 mTorr



🟢 - *ON-time*

🔴 - *OFF-time*

N. Britun et al, J. Appl. Phys. (2015).

Transport des espèces vers le substrat

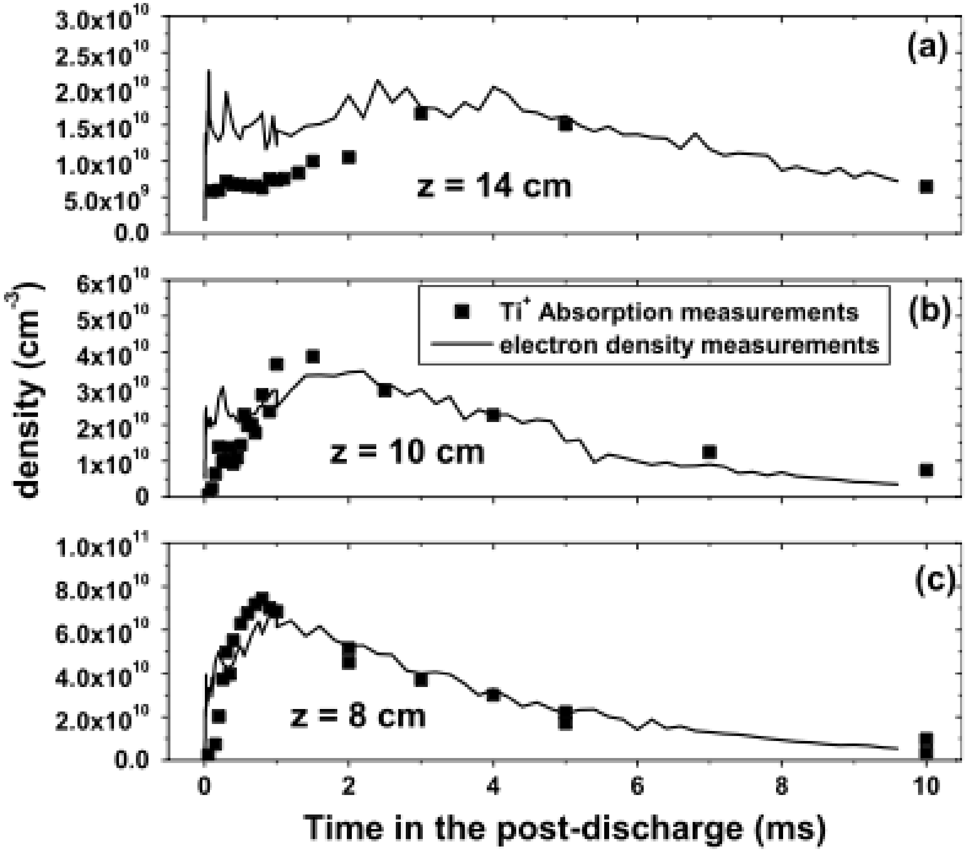
Espèces participant à la croissance du film = ions

Ces espèces doivent être transportées de la cible vers le substrat

Plusieurs paramètres influencent le transport

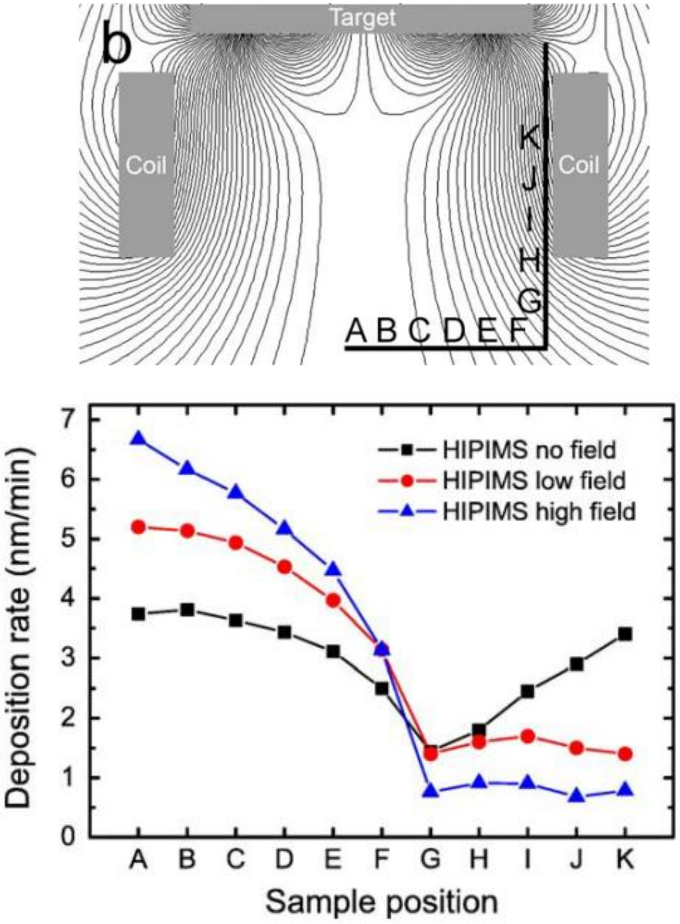
- Le champ magnétique
- L'éjection tangentielle des atomes
- La variation du potential plasma au cours du temps

Influence du champ magnétique



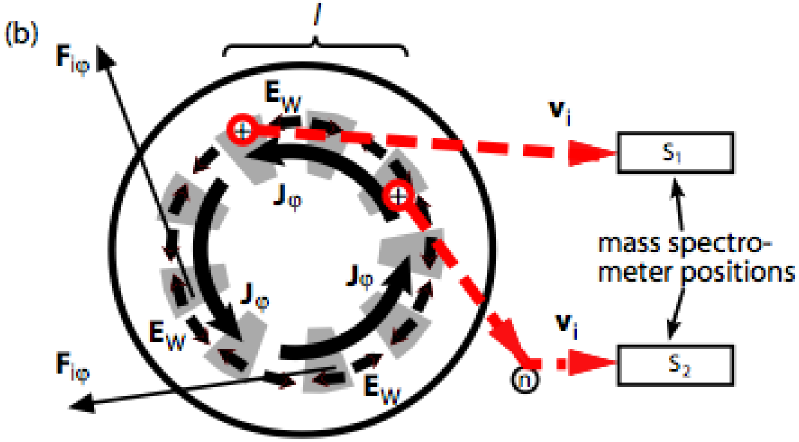
De Poucques et al, Plasma Sources Sci. Technol. (2006).

Effet du champ magnétique sur le transport des ions métalliques



Bohlmark et al, Thin Solid Films 2006.

Ejection tangentielle des ions métalliques



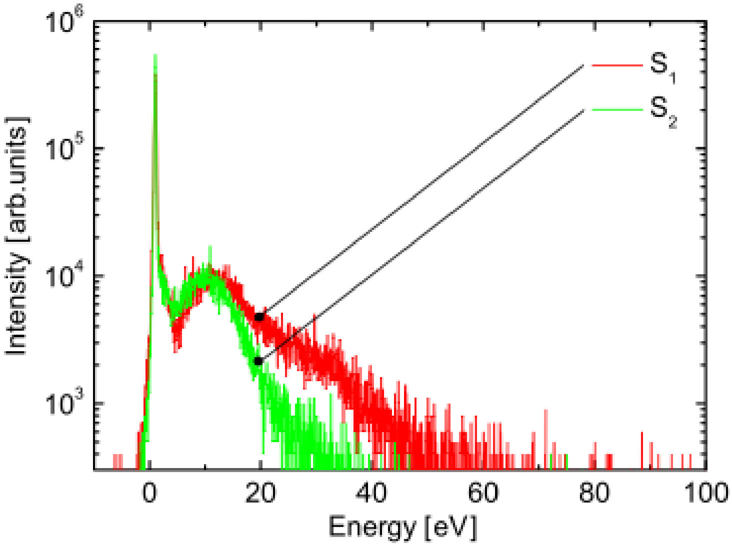


Figure 7. Comparison between Ti^+ion energies from two different sides of the HiPIMS race track, S_1 and S_2, as indicated in figure 1(*b*). The measurements were carried out at 0.80 Pa and $z = 0.01$ m using 500 V discharge pulses.

Lundin et al, Plasma Sources Sci. Technol. (2008).

Instabilité du plasma

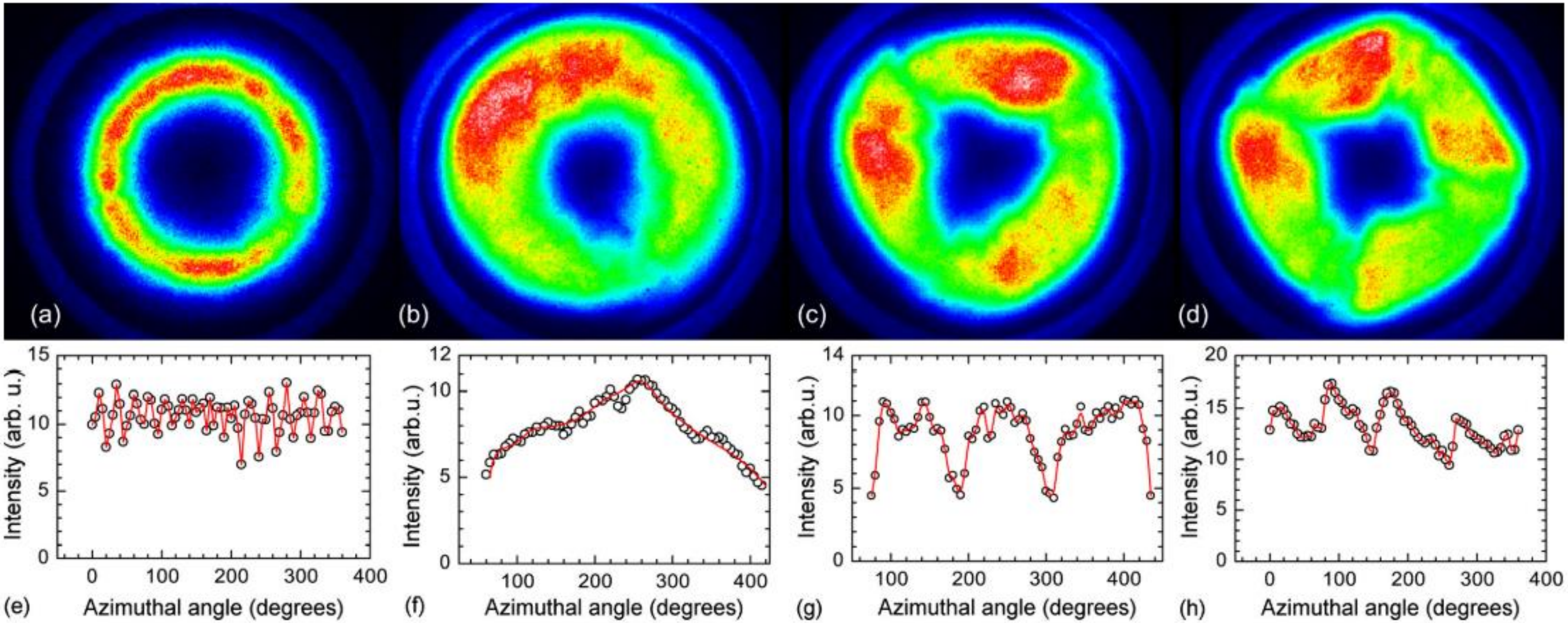


FIG. 2. (Color online) Influence of peak current density and Ar pressure on the discharge: (a) and (e) $J_d = 0.75$ A cm^{-2}, $P_{Ar} = 0.17$ Pa; (b) and (f) $J_d = 7.5$ A cm^{-2}, $P_{Ar} = 0.17$ Pa; (c) and (g) $J_d = 7.5$ A cm^{-2}, $P_{Ar} = 1.0$ Pa; and (d) and (h) $J_d = 7.5$ A cm^{-2}, $P_{Ar} = 1.7$ Pa. Upper row: fast photography frames (false color), lower row: total light intensity vs azimuthal angle corresponding to a circle along the centre of the racetrack. Angle is counted clockwise.

Ehiasarian et al, Appl. Phys. Lett., 2012

Instabilité du plasma

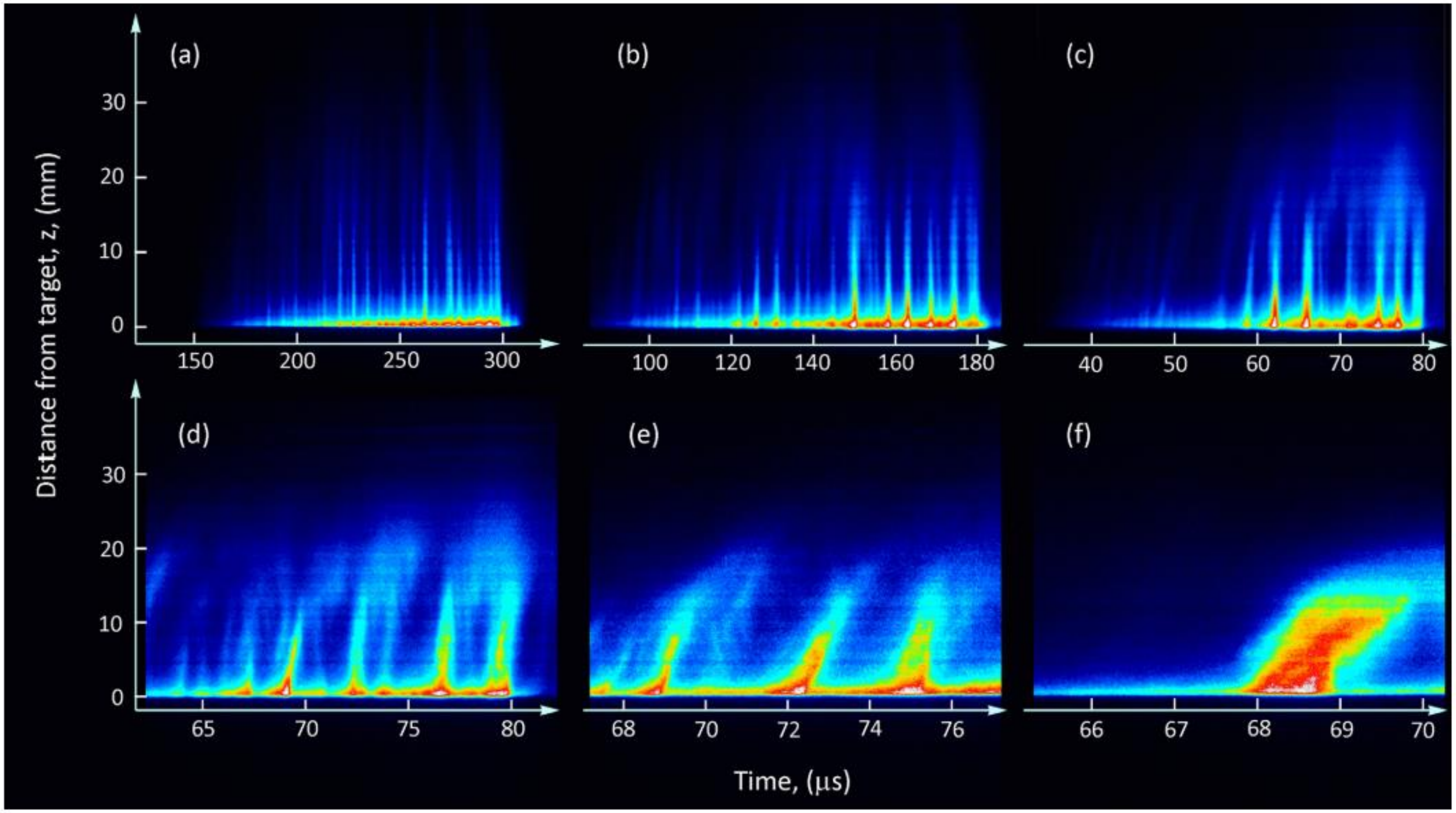
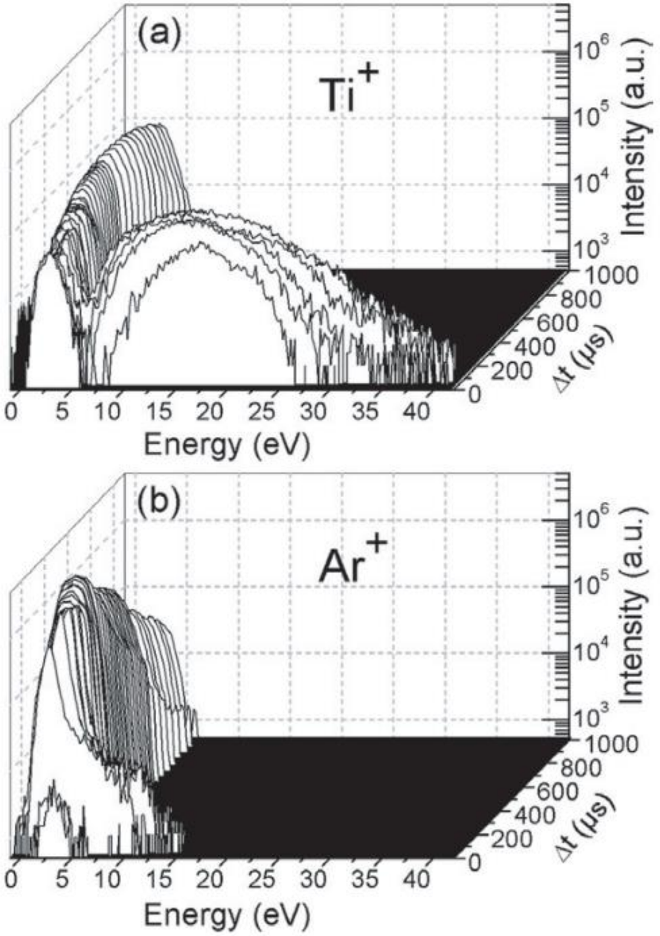
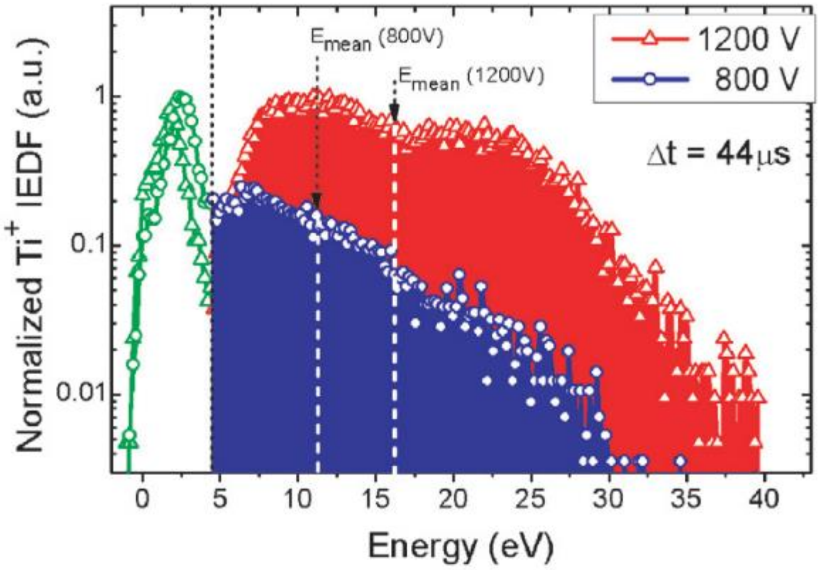


FIG. 1. Streak images of HiPIMS discharges (Ar 0.7 Pa, 50 pulses per second, 630–680 V, 500 A peak) using different pulse HiPIMS lengths and sweep durations: (a) 300 μs pulse, 200 μs sweep, (b) 180 μs pulse, 100 μs sweep, (c) 80 μs pulse, 50 μs sweep, (d) 80 μs pulse, 20 μs sweep, (e) 80 μs pulse, 10 μs sweep, and (f) 80 μs pulse, 5 μs sweep.

Ni et al. Appl. Phys. Lett., 2012

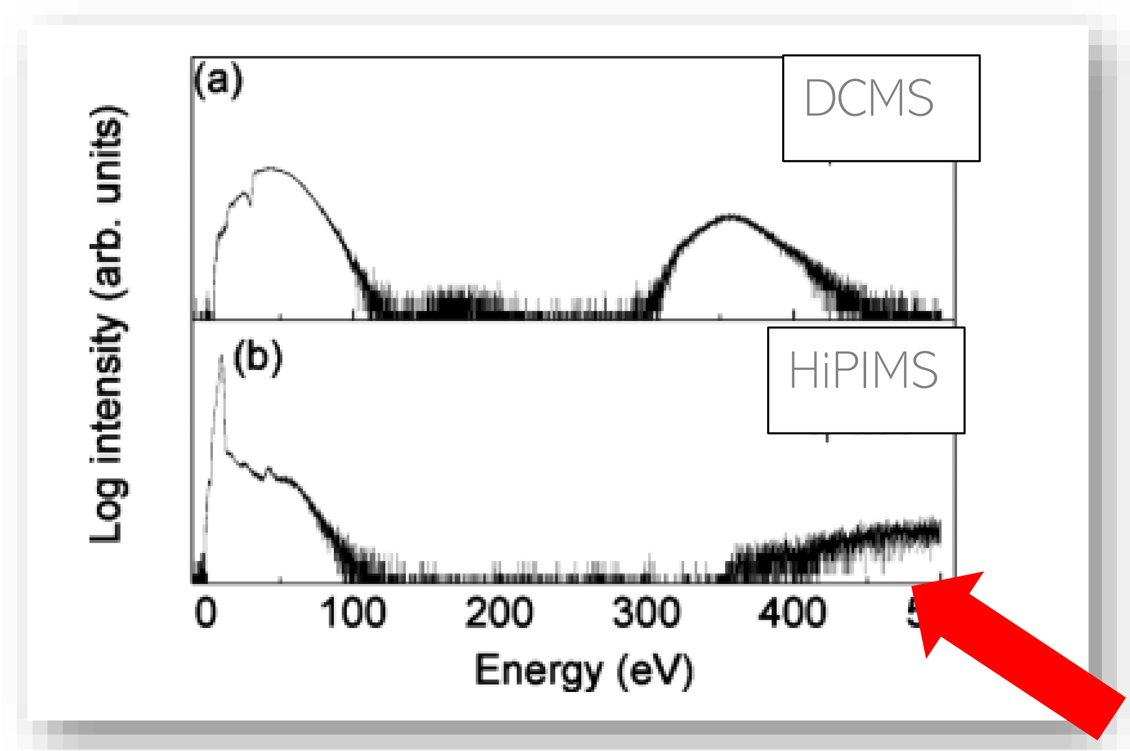
Fonction de distribution en énergie des ions métalliques





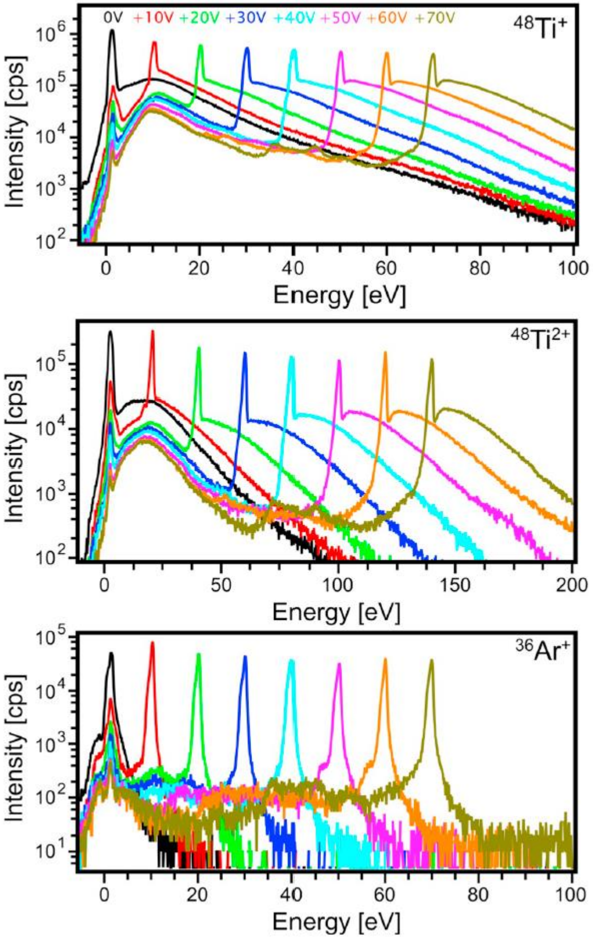
Palmucci, Konstantinidis et al, J. Phys D 2013

IEDF des ions O^-

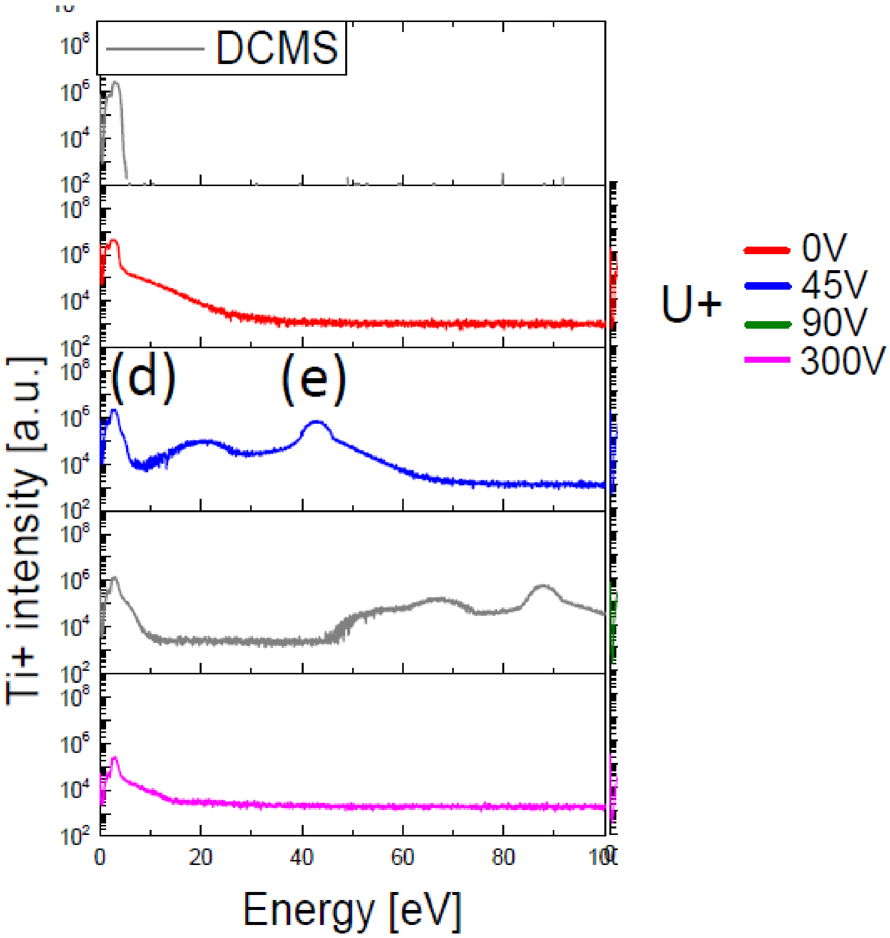


Sarakinos *et al*, J Phys D Appl Phys (2010)

IEDF pour l'HiPIMS bipolaire

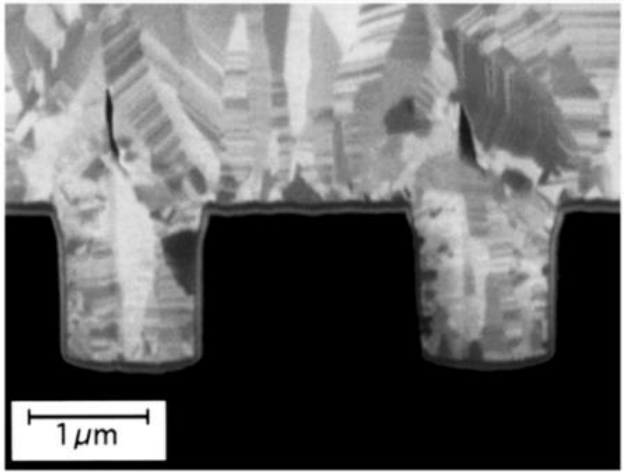


Keraudy et al Surf. Coat. Technol. 2018



M. Michiels, priv. comm. 2019

Dépôt conforme



Kouznetsov et al, Surf. Coat. Technol.,1999

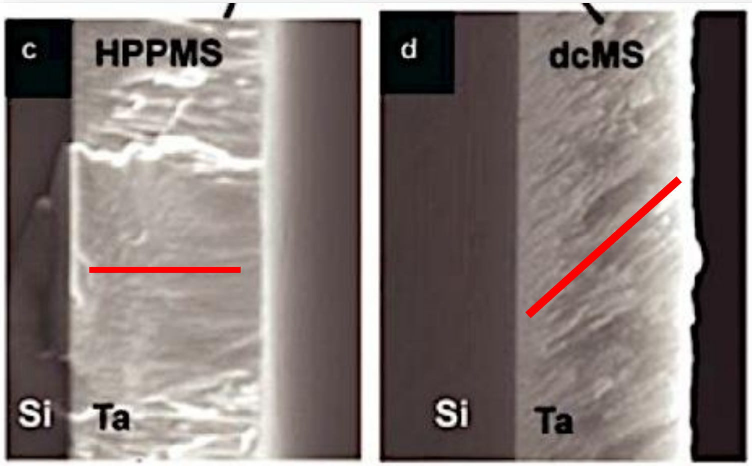


FIG. 1. SEM images of Ta films grown by HPPMS sputtering and dcMS near the opening of the trench (a) and (b), and approximately half way along the wall of the trench (c) and (d). Both films were grown at room temperature with a substrate bias of −50 V.

Alami et al, JVST A, 2007

Evolution microstructurelle: Effet du flux d'énergie normalisé

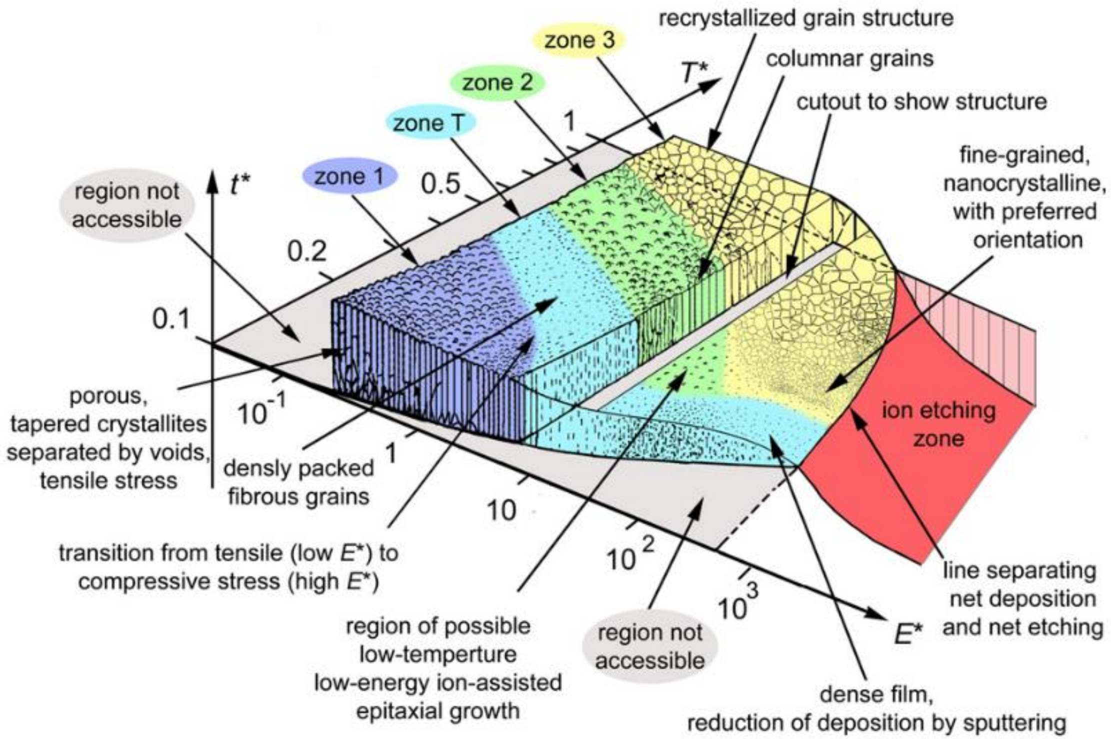
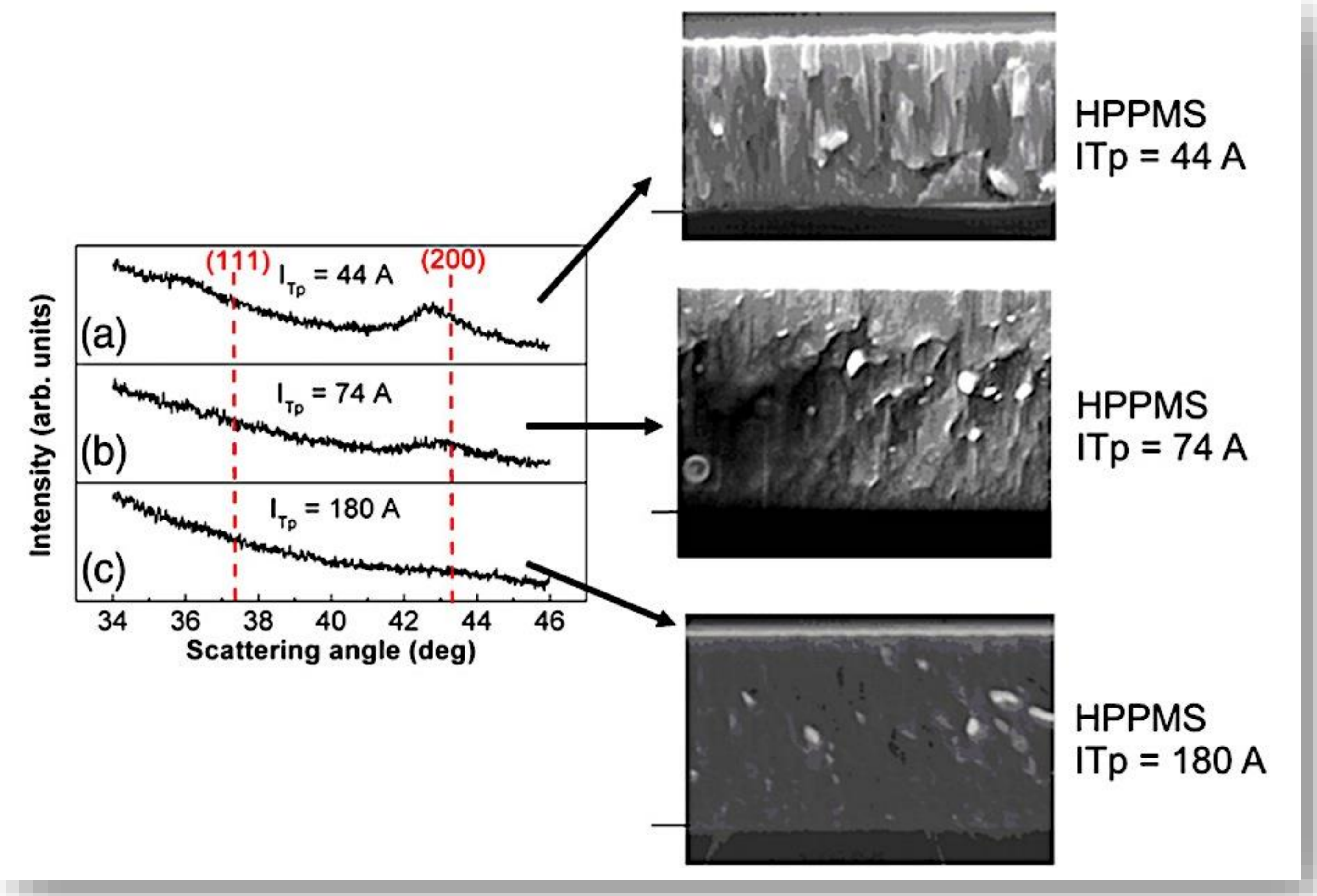


Fig. 1. Structure zone diagram applicable to energetic deposition; the generalized temperature T^* is given by Eq. (4), the normalized energy flux E^* by Eq. (5), and t^* represents the net thickness. The boundaries between zones are gradual and for illustration only. The numbers on the axes are for orientation only – the actual values depend on the material and many other conditions and therefore the reader should avoid reading specific values or predictions.

Anders , Thin Solid Films, 2010

Modification microstructurelle (CrN) : influence du flux d’ions



Alami et al, J. Phys. D: Appl. Phys. 2009

Films minces de TiO_2