High Power Impulse Magnetron Sputtering: 
A journey from early research to advanced processing

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founded in 1931

here are 7 (of now 10) Nobel Laureates

PAG @ Berkeley
Story Line

- Define HIPIMS. Why do we care?
- A very brief journey through 250 years of history
- HIPIMS: state of the art
HIPIMS: A Form of “Ionized Sputtering.”
One Approach to “Energetic Deposition.”

“What distinguishes HIPIMS from the long-practiced pulsed sputtering?”

Technical Definition:
HIPIMS is pulsed sputtering where the peak power exceeds the average power by typically two orders of magnitude.

(implies a long pause between pulses, hence the term “impulse”)

Physical Definition:
HIPIMS is pulsed sputtering where a very significant fraction of the sputtered atoms becomes ionized.

(implies that self-sputtering occurs, which may or may not be sustained by target ions)

Thorton’s Structure Zone Diagram for Sputtering

Contains the effects of energetic particle bombardment

Biasing: Controlling the Kinetic Energy of Ions upon Arrival on the Substrate Surface

- Final kinetic energy is enhanced by acceleration in sheath adjacent to the substrate surface

\[
E_i = E_0 + Qe(V_{\text{plasma}} - V_{\text{surface}})
\]

- High kinetic energy (\( \geq 1000 \text{ eV} \)) for pretreatment (ion etch)
- Low kinetic energy (10 eV...100 eV) for ion assist of growth
Generalized Structure Zone Diagram including the Effects of Plasma Assistance on Films

derived from Thornton’s diagram, 1974

\[ E^* = \text{normalized kinetic energy} \]
\[ t^* = \text{normalized film thickness} \]
\[ T^* = \text{normalized temperature and potential energy} \]

- **zone 1**: transition from tensile (low \( E^* \)) to compressive stress (high \( E^* \))
- **zone 2**: region of possible low-temperature, low-energy ion-assisted epitaxial growth
- **zone 3**: recrystallized grain structure
- **zone T**: columnar grains
- **ion etching zone**: fine-grained, nanocrystalline, with preferred orientation
- **region not accessible**: dense film, reduction of deposition by sputtering

A Union of Technologies

- Energetic Deposition
- Pulsed Power
- Magnetron Sputtering

High Power Impulse Magnetron Sputtering
Grove 1852: Sputtering

First sputtering was *pulsed* sputtering!

W. R. Grove, Phil. Mag. (1852) 498
Arthur Wright, 1877 deposited numerous films:
• Pt, Au, Co, Bi, Pd, Pb, Al, Sn, Mg, Zn, Cd, Ni, Co, Te, Fe
• describes the stability of films in the atmosphere

A.W. Wright, American J. Sci. - Third Series, vol. XIII, no. 78 (1877) 49

Pulsed Diode Sputtering (at relatively high pressure)
1884-1894: Edison’s arc plating patents

- First patent application claiming arc plasma deposition
- Although filed 1884, granted in part in 1894: limited to a continuous arc process in light of Wright’s pulsed work of 1877

T.A. Edison, ca. 1878
Plasmas can satisfy the need for better films...
Sputtering on its journey to an ion-assisted deposition process

- we know: densification of films can be accomplished by particle bombardment of the growing film
- to take advantage of the energetic particles in a sputtering process will require going to less collisions than what is done in diode sputtering → This is achievable by lowering the pressure.

But then how to overcome the issue

*mean free path for ionization >> system size*?

**Trapping and repeated “recycling” of charged particles!**

1. electrostatic trap
2. magnetic trap
3. combined electrostatic and magnetic traps
Magnetron as an Electron Trap

- target zone is a *magnetic mirror* as well as an *electrostatic reflector*
- electron *cyclotron motion* around field lines, resulting in closed azimuthal drift, the *magnetron motion*
- electrons cause ionization, and the “race track” appears under the drift zone due to sputtering by ions

1980s: Unbalanced Magnetron

- Unbalanced magnetic field allows electrons and ions to escape from target, providing a means of ion assistance.
- \( n_e \approx 10^{12} \), for up to a distance of 10 cm.

i-PVD: Magnetron Discharge with Ionization

RF power supply

vacuum pump

target

substrate

ICP

magnetron power supply

working gas supply

reactive gas supply

vacuum chamber

bias voltage


- conventional magnetron delivers (neutral) sputtered atoms
- flux of gas (argon) ions depends on “balancing” of the magnetic field
- Magnetron can be a plasma source when equipped with RF coil for post-ionisation
  - 70% ionised metal flux, high ion energy
  - more efficient at high pressures and low sputtering rates
High-Current Low-Pressure Quasi-Stationary Discharge in a Magnetic Field: Experimental Research

D. V. Mozgrin, I. K. Fetisov, and G. V. Khodachenko
Moscow Engineering Physics Institute, Kashirskoe sh. 31, Moscow, 115409 Russia
Received October 22, 1993; in final form, July 12, 1994

1993 a self-sputtering or HIPIMS mode!

planar magnetron

follow-up paper of same group:
1999: High Power Impulse Magnetron Sputtering

about 500 kW (!) peak power on a 15 cm diameter Cu target

Plenty of Evidence for Metal Ionization in HIPIMS

- Example: Ti target, \( \varnothing \) 5 cm, Ar, 850 V, 60 A after 50 \( \mu \)s
- \( m/q \) spectrum sampled for the 100-150 \( \mu \)s window of the 150 \( \mu \)s discharge

- Metal can dominate the plasma
- Singly charged ions are most frequent
- Even higher charge states are present

Look for this small change in voltage but huge effect in current!

Copper target, 2” magnetron

Runaway of Self-Sputtering

Condition of steady-state self-sputtering: 
\[ \Pi \equiv \alpha \beta \gamma = 1 \]

HIPIMS with Copper target in Argon

2” magnetron

Ion collector
HIPIMS without any gas: Pure Self-Sputtering in Vacuum

Ion Current at Substrate can be Very Large

Observed Exponential Growth of Available Ion Current with Voltage, and Reduction of Return Probability

Spectroscopic Diagnostics of HIPIMS

4 Pa, Ar, apply 2000 V

→ Video clip courtesy of Matej Hala.

2003: First HIPIMS experiments for Diamond-like Carbon

- Pulse width 60 - 120 µs
- Frequency 10 to 200 Hz
- Plasma impedance 0.5 - 3.0 Ω
- Charge voltage 500 - 2000 V
- ~ 5 kW average power
- Simmer supply capability to maintain low power plasma (<1 kW) between pulses
- $\alpha, \beta, \gamma < 1$, no sustained self-sputtering possible

Examples of HIPIMS Commercial Supplies and Systems
Summary

- HIPIIMS has its roots in
  - energetic deposition using plasmas
  - (magnetron) sputtering
  - pulsed power technology

- HIPIIMS: magnetron becomes a plasma source → self-ion assisted deposition for
  - densification
  - improvement of adhesion (often with pretreatment step)
  - control of phase and texture
  - influence stress
  - enabling certain coatings and properties, e.g. the “diamond-likeness” of DLC coatings

- HIPIIMS is still emerging yet has already become a commercially available technology; it will find greatest acceptance where the “value added” is needed for the application