PLD Sputtering Mechanisms

Pulsed Laser Deposition of Thin Films

Chrisey and Hubler, 1994

PLD Sputtering Mechanisms

- Sputtering also known as ablation or desorption
- Occurs when condensed phases (solids) are bombarded with ions, electrons or photons
- Occurs via primary and secondary mechanisms
- Primary mechanisms include collisional, thermal, electronic, exfoliational and hydrodynamic sputtering

PLD Sputtering Mechanisms

- Secondary mechanisms arise from bombardments that involving pulses of particles interact with each other
- Lose ‘memory’ of primary mechanism and become associated with secondary mechanisms
- Includes outflow with either reflection/recondensation or effusion with either reflection/recondensation
- Reflection and recondensation refer to the behavior of particles reflected back towards the surface
- Emitted particles tend to move according to laws of gas-dynamics

Thermal Sputtering

- Laser pulse bombards target to vaporize material
- Target has to be heated substantially above melting or boiling point
- Observed rate of sputtering during release time (τ_r) requires sufficiently high surface temperature (T)
- Release time (τ_r) may be shorter or longer than pulse time (τ)
- T cannot exceed Thermodynamic Critical Temperature (T_{ct})

Thermal Sputtering

Vaporizing flux = condensing flux

$$= p(2\pi k_b \mathrm{T})^{-1/2}$$

$$= p_0 e^{-\Delta H_v} (2\pi m k_b T)^{-1/2} \text{ atoms}/m^2 s$$

p- equilibrium vapor pressure

H_v- heat of vaporization

Thermal Sputtering

Depth/pulse = $\frac{p_0}{n_c}(2\pi m k_b)^{-1/2} * \int_0^\infty e^{-\Delta H_v/k_b T} T^{-1/2}\, dt$

n_c= number density of condensed phase (target)

Depth/pulse ~ $\frac{p_{atm}(T^{-\frac{1}{2}})\tau}{M^{1/2}\Delta H_v} * 1.53x10^6\ nm/pulse$

T- maximum surface temperature

M-molecular weight of vaporized species

We also assume top-hat pulse form (near uniform intensity in circular disk)

Thermal Sputtering

- Previously used expression to describe vaporization from a transiently heated target from conservation of energy (Batanov and Federov, 1973)

$$\frac{Depth}{pulse} = \frac{I\tau}{n_c \Delta H_v}$$

- Is actually incorrect; if $I\tau$=2. 5 J/cm^2 then we would see 1 $\mu m/pulse$ but we actually observe ~1 to 10 nm/pulse
- Due to actual loss rate being determined by kinetics, we must take into account the surface temperature T

Collisional Sputtering

- Direct beam-surface interaction
- Via momentum transfer from incident ions, electrons or photons
- Maximum Energy transfer (including relativistic effects)
- $E_2 = \frac{2E_1^2}{m_2c^2} + \frac{4M_1M_2E_1}{(M_1+M_2)^2}$
- $= \frac{E_1^2}{M_2} * 2.147x10^{-9} + \frac{4M_1M_2E_1}{(M_1+M_2)^2}\ eV$

Collisional Sputtering

- Assume displacement energy threshold of 25 eV
- In this case, photons do not directly sputter atoms from lattice structure
- High enough voltage electron microscope could displace some atoms

Collisional Sputtering

- Indirect collisional effects with photons
- Plasma produced during laser-surface interaction
- Laser-plasma interaction accelerates ions in plasma (100-1000ev)
- Ions then bombard nearby surfaces

Collisional Sputtering

- Produces substrate erosion
- Particles emitted from laser bombarded target cause erosion on nearby surfaces
- Cd target bombarded by 4-10 J/cm^2 pulses
- Vaporize 22 nm/pulse
- Ions accelerated by laser-plasma interaction caused erosion on order of 0.02 to 0.12 nm
- Still one or two orders of magnitude smaller

Collisional Sputtering

- Cone formation- if surface undergoing bombardment is non-uniform then it will undergo cone formation due to angular dependence of sputtering
- Could also be caused by impurities, scattering off dust, etc
- Ultimately due to surface irregularities directing ions to their bases

Electronic Sputtering

- Refers to group of processes that involve excitation or ionization
- Can occur due to ion explosions, the 'hole-pair' mechanism, defect formation or surface plasmon interaction
- Normally confined to dielectrics and wide bandgap semiconductors except when due to plasmons

Electronic Sputtering

- Sufficiently high laser-pulse energy will cause dense electron excitation in surface
- In Al_2O_3, excitation can be as high as $n_e = 10^{22}\ cm^{-3}$ (excited electron number density)
- Increases total Energy of each atom by $n_e E_{gap}/n_c$
- Since $E_{gap} \sim 9ev$ and $n_c \sim 4.7x10^{22}$, the pulse increases the energy of each atom by ~2eV
- Sufficient to increase vapor pressure by at least an order of magnitude or render lattice unbound

Electronic Sputtering

- Related to rapid energy deposition model
- Explains response of solids to incident particles such as laser pules, fission fragments, electron pulses or small accelerated dust particles
- System makes transition from tightly bound solid to dense, repulsive gas
- Individual atoms expelled