

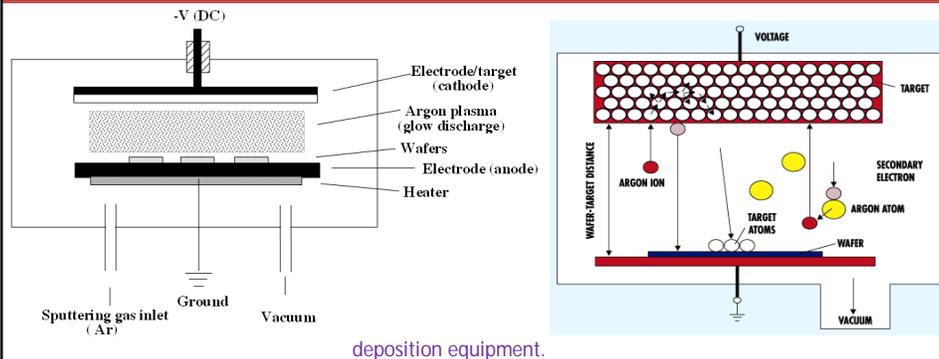
Thin film deposition

1. Introduction to thin film deposition.
2. Introduction to chemical vapor deposition (CVD).
3. Atmospheric Pressure Chemical Vapor Deposition (APCVD).
4. Other types of CVD (LPCVD, PECVD, HDPCVD...).
5. Introduction to evaporation.
6. Evaporation tools and issues, shadow evaporation.
7. Introduction to sputtering and DC plasma.
8. Sputtering yield, step coverage, film morphology.
9. Sputter deposition: reactive, RF, bias, magnetron, collimated, and ion beam.

NE 343: Microfabrication and thin film technology
 Instructor: Bo Cui, ECE, University of Waterloo; <http://ece.uwaterloo.ca/~bcui/>
 Textbook: Silicon VLSI Technology by Plummer, Deal and Griffin

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Sputter deposition



- Plasma is needed to make the gas conductive, and generated ions can then be accelerated to strike the target.
- Higher pressures than evaporation: 1-100 mTorr.
- Better at depositing alloys and compounds than evaporation.
- The plasma contains \approx equal numbers of positive argon ions and electrons as well as neutral argon atoms. Typically only $<0.01\%$ atoms are ionized!

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Sputtering process

- Sputtering process can be run in DC or RF mode (insulator must be run in RF mode)
- Major process parameters:
 - Operation pressure (~1-100mTorr)
 - Power (few 100W)
 - For DC sputtering, voltage -2 to -5kV.
 - Additional substrate bias voltage.
 - Substrate temperature (20-700°C)
- In addition to IC industry, a wide range of industrial products use sputtering: LCD, computer hard drives, hard coatings for tools, metals on plastics.

It is more widely used for industry than evaporator.



Targets for sputter deposition.

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Sputter deposition advantages

Advantages:

- Able to deposit a wide variety of metals, insulators, alloys and composites.
- Replication of target composition in the deposited films.
- Capable of in-situ cleaning prior to film deposition by reversing the potential on the electrodes → etching the substrate .
- Better film quality and step coverage than evaporation.
- More reproducible deposition control – same deposition rate for same process parameters (not true for evaporation), so easy film thickness control via time.
- Can use large area targets for uniform thickness over large substrates.
- Sufficient target material for many depositions.
- No x-ray damage.

Disadvantages:

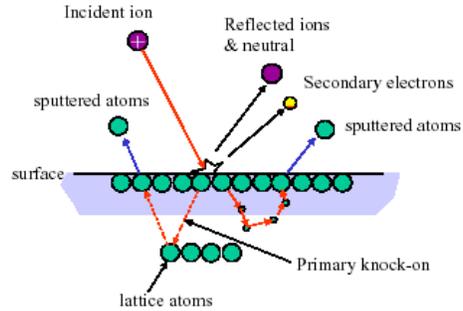
- Substrate damage due to ion bombardment or UV generated by plasma.
- Higher pressures 1 –100 mtorr (10^{-5} torr in evaporation), more contaminations unless using ultra clean gasses and ultra clean targets.
- Deposition rate of some materials quite low.
- Some materials (e.g., organics) degrade due to ionic bombardment.
- Most of the energy incident on the target becomes heat, which must be removed.

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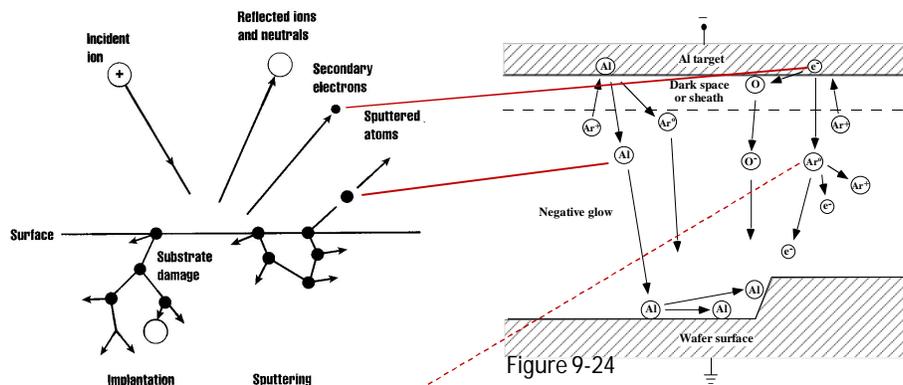
Mechanisms of sputtering

The ion impact may set up a series of collisions between atoms of the target, possibly leading to the ejection of some of these atoms. This ejection process is known as sputtering.

Here we are interested in sputter deposition. Of course sputter can also be used as an etching method (the substrate to be etched will be the 'target'), which is called sputter etching.



Mechanisms of sputtering



After collision ionization, there are now TWO free electrons. This doubles the available electrons for ionization. This ongoing doubling process is called "impact ionization", which sustains a plasma.

On the left side, sputter off an Al atom. On the right side, generate secondary electrons, which are accelerated across the sheath region and 1) ionize/excite an Ar; or 2) ionize an impurity atom, here O, to generate O⁻ (for Ar, always positive ion Ar⁺). This O⁻ is accelerated toward substrate and may go into the film.

DC plasma

Plasma is ionized gas, with nearly equal number of ions and electrons, plus neutrals (un-ionized molecules including those at ground state and excited state).
 Glow is due to de-excitation of excited Ar.
 So glow only exists where there are lots of electrons to excite Ar.

Cathode glow region: very close to cathode, secondary electrons are created by Ar bombardment of target material.

Cathode dark space/sheath: electrons pass too fast.

Anode sheath: electrons lost to anode due to its faster *random* movement.

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Requirement for self-sustained discharge (plasma)

Ions make (secondary) electrons when they bombard the target, and electrons make ions when they collide with Ar → self sustained discharge.

Condition for *sustaining* plasma: $pd > 0.5$ (cm·Torr).
 For instance, typical target-substrate spacing $d \sim 10$ cm, need $p > 50$ mTorr (actually sputter deposition is usually conducted at <10 mTorr, due to magnetron...).

Condition for *igniting* the plasma.
 Too large $P \times d$ leads to too many collisions that prevent electron energy buildup.
 Too small $P \times d$, there will be too few collisions (electron just goes to the wall without ionizing a molecule or atom), and too few ions to bombard and generate secondary electrons.
 Once the plasma is ignited, it is very conductive, thus voltage drops to order 100 V only.

Figure 2.7 The dc breakdown voltage as a function of gas pressure P and electrode spacing d for plane parallel electrodes in air and some other gases. Such curves are determined experimentally and are known as *Paschen curves*.

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Reactive sputtering

Sputtering metallic target in the presence of a reactive gas mixed with inert gas (Ar).

- Sputtering a compound target may not give what one wants.
- This doesn't mean reactive sputtering will give what one wants – it is just one more thing to try with.
- Certainly reactive sputtering can be done using DC sputtering, whereas compound target (insulating) can only be used for RF sputtering.
- Chemical reaction takes place on substrate and target.
- Can “poison” target if chemical reactions are faster than sputter rate.
- Need to adjust reactive gas flow to get good composition (e.g. SiO₂ rather than SiO_{2-x}) without incorporating excess gas into film.

A mixture of inert + reactive gases used for sputtering:

Oxides – Al₂O₃, SiO₂, Ta₂O₅ (O₂ mixed with Ar)

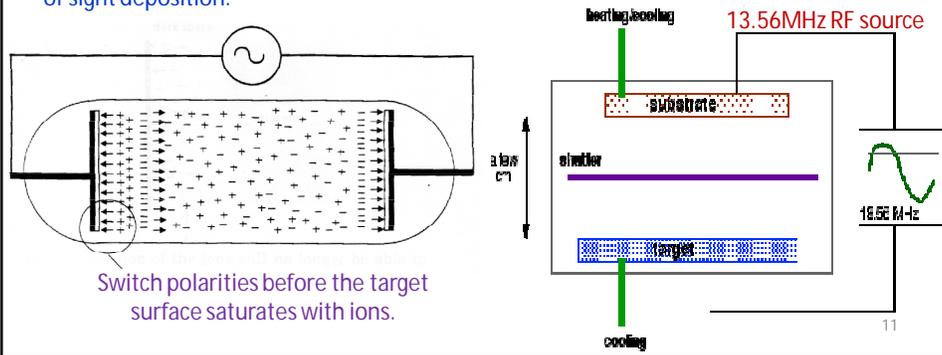
Nitrides – TaN, TiN, Si₃N₄ (N₂, NH₃, mixed with Ar)

Carbides – TiC, WC, SiC (CH₄, C₂H₄, C₃H₈, mixed with Ar)

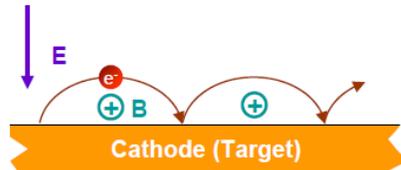
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RF (radio frequency) sputter deposition

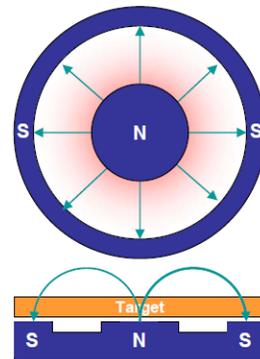
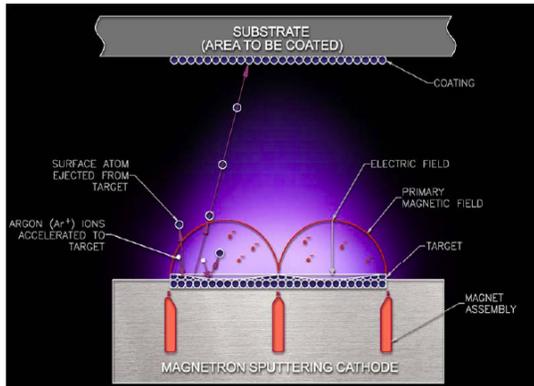
- Good for insulating materials because, positive charge (Ar^+) build up on the cathode (target) in DC sputtering systems. Alternating potential can avoid charge buildup
- When frequencies less than $\sim 50\text{kHz}$, both electrons and ions can follow the switching of the anode and cathode, basically DC sputtering of both surfaces.
- When frequencies well above $\sim 50\text{kHz}$, ions (heavy) can no longer follow the switching, and electrons can neutralize positive charge buildup on each electrode during each half cycle.
- As now electrons gain energy directly from RF powder (no need of secondary electrons to maintain plasma), and oscillating electrons are more efficient to ionize the gas, RF sputter is capable of running in lower pressure (1-15 mTorr), so fewer gas collisions and more line of sight deposition.



Magnetron sputtering

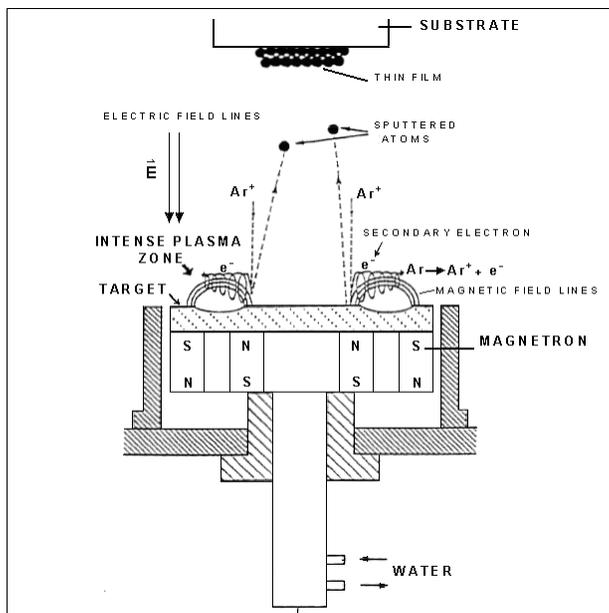


Orbital motion of electrons increases probability that they will collide with neutral species and create ions.



Magnetron sputtering for high density of plasma near target.

Magnetron sputtering



Magnetron sputtering

- In DC & RF sputtering, the efficiency of ionization from energetic collisions between the electrons and gas atoms is low.
- Most electrons lose energy in non-ionizing collisions or are collected by the electrodes.
- Oscillating RF fields increasing ionization efficiency marginally.
- Hence, deposition rates are low.
- To increase deposition rates, magnets are used to increase the percentage of electrons that take part in ionization events, increasing the ionization efficiency.
- A magnetic field is applied at right angles to the electric field by placing large magnets behind the target.
- This traps electrons near the target surface and causes them to move in a spiral motion until they collide with an Ar atom.
- The ionization and sputtering efficiencies are increased significantly due to increase in Ar^+ ions - **deposition rates increase by 10-100x, to 1 μm per minute.**
- Unintentional wafer heating is reduced since the dense plasma is confined near the target and ion loss to the wafers is less.
- Magnetron sputtering can be done in DC or RF, but more often it is done in DC as cooling of insulating targets is difficult in RF systems.

Comparison of evaporation and sputtering

Property	Evaporation	Sputtering
Thickness control	possible	easy
Materials	limited	almost unlimited
Cleanness	good	good
Substrate heating	no	yes
Surface roughness	little	ion bombardment
Selfcleaning	not possible	pole reversal
Multilayers	different holders	different targets
Adhesion	medium	good
Shadowing effects	large	small
Film properties	difficult to control	can be controlled
Equipment cost	medium	expensive

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Comparison of evaporation and sputtering

EVAPORATION	SPUTTERING
low energy atoms	higher energy atoms
high vacuum path <ul style="list-style-type: none"> • few collisions • line of sight deposition • little gas in film 	low vacuum, plasma path <ul style="list-style-type: none"> • many collisions • less line of sight deposition • gas in film
larger grain size	smaller grain size
fewer grain orientations	many grain orientations
poorer adhesion	better adhesion

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Comparison of evaporation and sputtering

Evaporation	Sputtering
Low energy atoms (~ 0.1 eV)	High energy atoms / ions (1 – 10 eV) • denser film • smaller grain size • better adhesion
High Vacuum • directional, good for lift-off • lower impurity	Low Vacuum • poor directionality, better step coverage • gas atom implanted in the film
Point Source • poor uniformity	Parallel Plate Source • better uniformity
Component Evaporate at Different Rate • poor stoichiometry	All Component Sputtered with Similar Rate • maintain stoichiometry

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Comparison of evaporation and sputtering

	Evaporation	Sputtering
Rate	Thousand atomic layers per second (e.g. 0.5 $\mu\text{m}/\text{min}$ for Al)	One atomic layer per second
Choice of materials	Limited	Almost unlimited
Purity	Better (no gas inclusions, very high vacuum)	Possibility of incorporating impurities (low-medium vacuum range)
Substrate heating	Very low	Unless magnetron is used substrate heating can be substantial
Surface damage	Very low, with e-beam x-ray damage is possible	Ionic bombardment damage
In-situ cleaning	Not an option	Easily done with a sputter etch
Alloy compositions, stoichiometry	Little or no control	Alloy composition can be tightly controlled
X-ray damage	Only with e-beam evaporation	Radiation and particle damage is possible
Changes in source material	Easy	Expensive
Decomposition of material	High	Low
Scaling-up	Difficult	Good
Uniformity	Difficult	Easy over large areas
Capital Equipment	Low cost	More expensive
Number of depositions	Only one deposition per charge	Many depositions can be carried out per target
Thickness control	Not easy to control	Several controls possible
Adhesion	Often poor	Excellent
Shadowing effect	Large	Small
Film properties (e.g. grain size and step coverage)	Difficult to control	Control by bias, pressure, substrate heat

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Comparison of typical thin film deposition technology

Process	Material	Uniformity	Impurity	Grain Size	Film Density	Deposition Rate	Substrate Temperature	Directional	Cost
Thermal Evaporation	Metal or low melting-point materials	Poor	High	10 ~ 100 nm	Poor	1 ~ 20 A/s	50 ~ 100 °C	Yes	Very low
E-beam Evaporation	Both metal and dielectrics	Poor	Low	10 ~ 100 nm	Poor	10 ~ 100 A/s	50 ~ 100 °C	Yes	High
Sputtering	Both metal and dielectrics	Very good	Low	~ 10 nm	Good	Metal: ~ 100 A/s Dielectric: ~ 1-10 A/s	~ 200 °C	Some degree	High
PECVD	Mainly Dielectrics	Good	Very low	10 ~ 100 nm	Good	10 - 100 A/s	200 ~ 300 °C	Some degree	Very High
LPCVD	Mainly Dielectrics	Very Good	Very low	1 ~ 10 nm	Excellent	10 - 100 A/s	600 ~ 1200 °C	Isotropic	Very High