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Practical Process Tips

Increasing Sputter Rates

When sputtering dielectric targets using RF power, it is quite possible for the maximum deposition rate on the substrate to be less than 0.1 Å/sec. That is, depositing a film 100nm thick may take over 2½ hours. It is no surprise, therefore, that we are frequently asked, "How can I increase the sputter rate?"

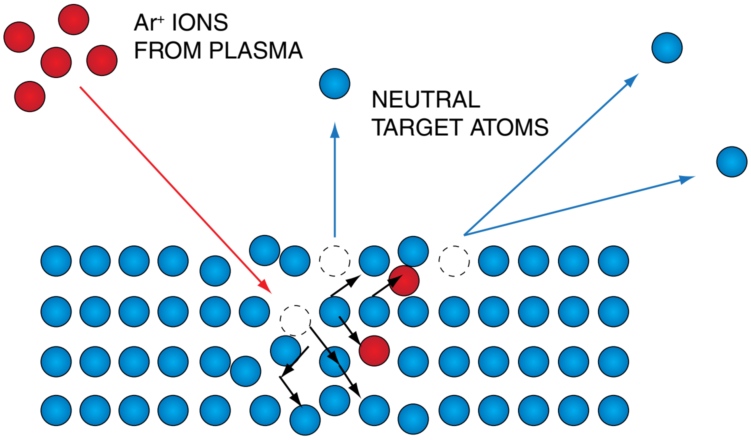
Actually, what the questioner wants is to increase the deposition rate, but we're not about to argue semantics with a frustrated researcher.

(But to segue into semantics for a moment: we will use *sputter* as the adjectival form, as in *sputter yield*, *sputter rate*, *sputter gun*, rather than *sputtering yield* etc.)

In this issue we review ways to increase deposition rates and look at conditions where maximizing one parameter inadvertently affects something else.

While the substrates can be static or rotating, these suggestions apply only to circular sputter guns with flat disc targets and stationary magnet assemblies. Sputter guns with targets of other shapes and configurations, moving magnet assemblies, and linear sputter guns, have their own performance attributes that are not directly addressed here.

BASIC MECHANISM OF SPUTTERING



The Ar+ ions have sufficient energy to eject target atoms into gas phase

Sputter sources in co-deposition 'action'

Sputter Yield

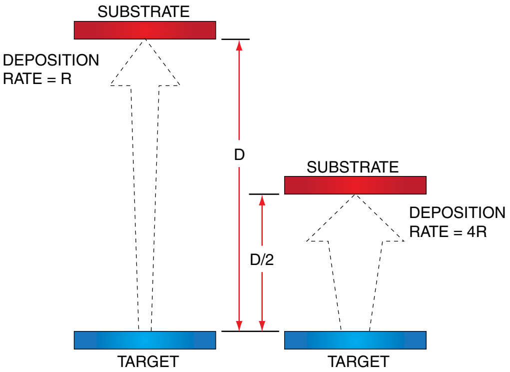
First, we must understand that each material has its own characteristic sputter yield – the number of atoms (or molecules) leaving the target for each ion that hits it. The sputter yield value depends on: the material; the mass of the incoming ion; the voltage through which the ion is accelerated; and its angle of incidence on the target.

For Ar+ ions striking a target at 45° through a potential of 500eV, the sputter yields of most elements are between 1 - 10, roughly. (See the National Physics Labs calculated list: *http://www.npl.co.uk/nanoscience/surface-nanoanalysis/products-and-services/sputter-yield-values*)

Materials that are chemical compounds such as oxides can have much lower sputter yields! For example, Maissel and Glang's book *Handbook of Thin Film Technology* quotes the sputter yield for SiO_2 as 0.13 and Al_2O_3 as 0.04.

Extending the concept of sputter yield, we will later refer to a material's sputter rate, which is its sputter yield multiplied by the ion current to the target.

Throw Distance Changes



A representation of the effect of deposition rate when the Throw Distance is halved

Reducing the target-to-substrate distance (often called *throw distance*) is a simple, direct way to increase deposition rate. To fully understand this effect, the angular distribution of sputtered particles must be known. Regrettably, this is a complex subject since material is ejected from a circular 'trench' around the target and terms like *over-cosine* and *under-cosine* are used in the literature to describe a sputtered material's flux distribution.

For these notes, however, it is sufficient to understand that the sputtered particles' arrival rate (per unit area of substrate) varies as the inverse square of the throw distance. That is, halving the throw distance quadruples the material's arrival rate at the substrate and the film's thickness grows at 4x the previous rate!

However, it is important to consider the shorter throw distance's affect on the film's (thickness) uniformity. If, for example, material leaves the target in roughly a cosine distribution pattern, then the larger the throw distance, the higher the number of thermalizing collisions between sputtered atoms and sputter gas atoms. These collisions tend to 'flatten out' the cosine distribution making the deposition more uniform across the substrate. Since a shorter throw distance means fewer collisions, film uniformity at shorter distances may be worse.

In addition, at shorter throw distances substrates may see: higher energy sputter particles; more stray electrons; more plasma ions and 'hot' neutrals; and higher thermal radiation heat transfer from the plasma and target surface. So the adverse effects of a shorter throw distance include:

- Excessive substrate outgassing
- Increase in compressive stress in the growing film
- Films beneath the present one damaged by electron bombardment
- Substrate melting!

However, shorter throw distances (and, therefore, higher substrate temperatures) can have beneficial effects too:

- Films may grow as successive monolayers (called Frank—van der Merwe growth, a frequently desirable nucleation mode)
- The film's tensile stress may be reduced
- Film adhesion may improve due to the higher energy of arriving atoms
- Films may be 'densified' by bombardment with higher energy plasma ions and 'hot' neutrals

Increasing Power

Doubling the power applied to the target roughly doubles the sputter rate and this always appears to be the 'easy option' when faced with low deposition rates.

Kurt J. Lesker Company RF power supply for non-conducting targets

Unfortunately, arbitrarily increasing power has many adverse effects. All power applied to the gun must dissipate somewhere in the system. It is claimed that roughly 75% ends up heating the gun's cooling water. That is, 75% of the total power dumped into the target's front face must transfer through the target to reach the water! Clearly, the target's thermal conductivity, thermal coefficient of expansion, mechanical strength characteristics, and melting point, are critical issues.

- Thermal conductivity helps determine the temperature difference between the target's front and rear faces. The larger that difference the higher the thermal stress in the material

Power & Power Density

Although we quote the power applied to a target, the critical quantity is really *power density*, which is the power applied divided by the target's surface area. Let us suppose the target in a 5cm (2") gun accepts 100W maximum power. Then, how can the same target material in a 10cm (4") gun accept 400W?

The table shows that despite the large change in maximum power, the two targets have identical power densities.

Diameter	**Area**	**Power**	**Power Density**
cm	cm^2	W	W/cm^2
5	19.6	100	100/19.6 = 5.1
10	78.5	400	400/78.5 = 5.1

Maximum Power Levels

So, how do I find the 'appropriate maximum power' for my target?

With patience and a 'trick'. The first time a new target material is sputtered, slowly ramp the power until the power density (*see **Power & Power Density***) on the target is:

Highly conductive (e.g., Al, Cu)	15 W/cm^2
Moderately conductive (e.g., Ti, NiCr)	9 W/cm^2
Conductive oxide (e.g., ITO, AZO)	3 W/cm^2
Ceramic insulator (e.g., HfO_2, $BaTiO_3$)	3 W/cm^2
Low melting metal (e.g., In, Sn)	2 W/cm^2

Let the target soak for a minute or two at whatever power that turns out to be. Then slowly increase *power* (not power density) by 5W and monitor the voltage for another minute. If it remains stable, ramp up another 5W and watch it for another minute.

Continue these 5W ramp/1 minute voltage monitoring steps until the voltage starts to rise. Immediately back off the power by 5W and monitor the voltage. If it remains stable for 5 minutes, you have found the appropriate maximum power for that target in that sputter gun. If, however, the voltage still rises, back off in further increments of 5W until it does stabilizes. (*But note **Caveat to the Trick**.*)

Motto: If in doubt when starting out, make it your propensity to lower power density!

- Thermal coefficient of expansion partly determines the mechanical stresses resulting from the thermal stress
- Mechanical strength determines how the mechanical stresses are dissipated (usually by bowing, warping, chipping, or cracking)
- Melting point (obviously) determines if the target will melt at the temperature generated by the applied power level – and a molten target can ruin a sputter gun

Another major concern is the 'thermal conductance' of the interface between the target's rear face and the sputter gun's cooling well. Results tabulated in *A Heat Transfer Textbook* by Lienhard & Lienhard indicate the thermal conductance between two lightly clamped, flat metal surfaces is (a) not very high, and (b) depends significantly on air between the surfaces.

Evacuate that interface – that is, put the sputter gun under operating conditions – and the thermal conductance of the interface between the target and the cooling well may drop to 1/20th to 1/50th of its 'with air' value.

Some target materials are so fragile they crack no matter what sputter power is used. Bonding such materials to copper backing plates may allow their continued use even though cracked. However, if pieces chip off or the cracks become wide enough to expose bonding agent or copper backing plate, the target must be replaced.

Too high sputter power is the most common cause of target and sputter gun damage. Given the target/interface thermal limitations, such damage can be reduced/eliminated by using an *appropriate* maximum power (*see **Maximum Power Levels***). However, 'appropriate' often equates to 'low' and low power means low deposition rates.

One final point about applying power to a target. Once the appropriate power has been established for a given target/gun, **never** switch on and immediate increase power to that value! Always increase power *slowly* to its maximum value through a series of *ramps* and *soaks*.

Sputter Gas Pressure

Lowering the sputter gas pressure causes a modest increase in deposition rate by a two-fold mechanism:

- Sputtered atoms leaving the target will undergo fewer thermalizing collisions.They are less likely to scatter 'sideways' and a larger percentage will continue to the substrate, slightly increasing the deposition rates
- In power control mode, using either RF or DC power, the plasma-to-target voltage will increase slightly. Ions bombarding the target will, therefore, have a higher energy which slightly increases the sputter yield and consequently the sputter rate.

One potential side-effect of lowering the gas pressure is a change in film uniformity. Whether it improves or worsens is typically not predictable because there are many factors involved. But one obvious aspect is a reduction in the number of thermalizing collisions.

Caveat to the Trick

Reactive metal targets such as Al and Mg are initially covered by a thin oxide coating. Before that layer 'burns' off, the target will arc, spit, and most importantly, run at a low voltage. Once that oxide layer has gone, the voltage will rise sharply to a new level.

It is this 'clean target' voltage level that you are trying to stabilize with the trick – not the initial low voltage.

An adverse effect of lower gas pressure/higher plasma-to-target voltage combination is the greater likelihood of arcs occurring near the target.

Increasing Target Size

As a method of increasing deposition rate, this option is not easily implemented and is expensive since it requires a new sputter gun, sufficient room to install it in the chamber, and possibly a larger power supply.

For a given power density (*see* ***Power & Power Density***), the larger the target diameter the higher the sputter rate. The explanation is simple. A larger target diameter means a larger sputter trench area and, for a given power density, increased trench area means increased sputter rate.

Number of Guns

The majority of R&D deposition systems have more than one sputter gun installed. Typically, the user installs different target materials in each gun. However, putting the same target material on two or more guns and operating them simultaneously can double, triple, etc. the sputter rate and resulting deposition rate.

The drawback is, many multi-gun systems were not built for co-deposition work and have just one power supply. Buying additional supplies for simultaneous operation may make this option expensive.

Conclusion

Yes, there are ways to increase deposition rates. Unfortunately the easy *winding-up-the-power* option, if misused, at best leaves your targets looking a little sad. At worst, your sputter gun splutters to a stop, water leaks into the chamber, or the power supply fries. No, I jest! At worst, all three happen simultaneously.

Cerium oxide target bonded to copper backing plate but sputtered at a power that melted the indium bond and cracked the target

3” diameter Indium tin oxide target sputtered at 1000W (roughly 7x the maximum recommended power)

Aluminum doped zinc oxide target given the ‘tough love’ treatment of inadequate cooling (at the 10:00 o’clock position) and excessive power

As always, if you have questions or comments email *techinfo@lesker.com* and they will be forwarded to the author.

Lesker On The Road

Date	Show	City	State/Country	Booth Number
June 27-29	ACNS	Ottawa	Canada	–
June 28-July 2	NANO 2010 Nanotechnology Conference	Poznan	Poland	–
June 28-30	WODIM 16th Workshop on Dielectrics in Microelectrons	Bratislava	Slovakia	–
June 30	IOP Perspectives on Materials and Technologies for Photovoltaics	London	United Kingdom	–
July 6-7	HIPIMS	Sheffield	UK	–
July 7-9	CONF IS-FOE (International Symposium on Flexible Organic Electronics)	Halkidiki	Greece	–
July 13 - 15	Semicon West 2010	San Francisco	CA	2021
July 13 - 15	Intersolar N.A.	San Francisco	CA	8139

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