Contamination in vacuum coatings due to water vapor

Donald J. McClure
Acuity Consulting and Training

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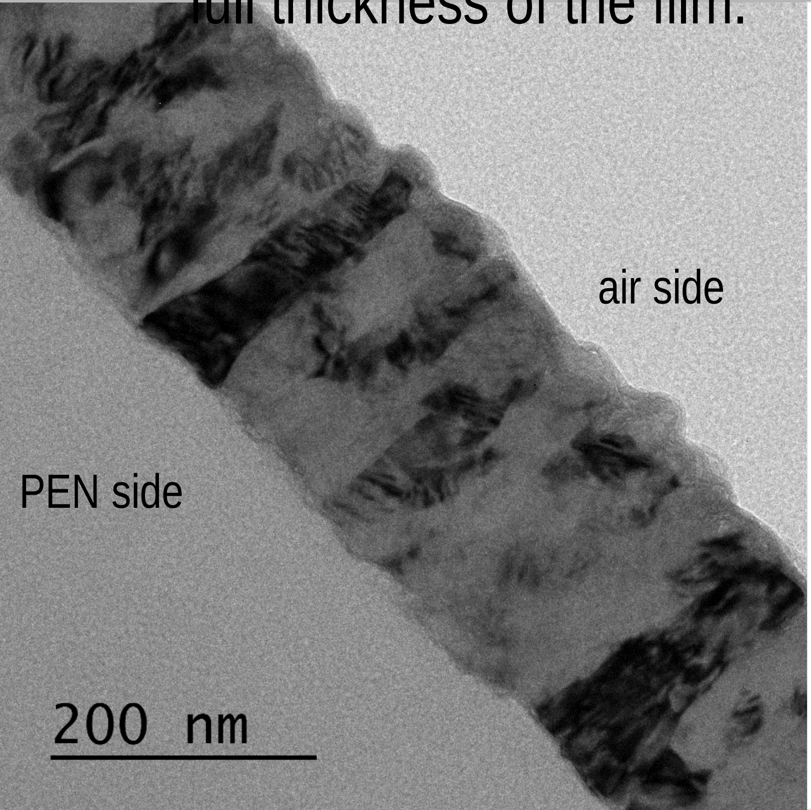
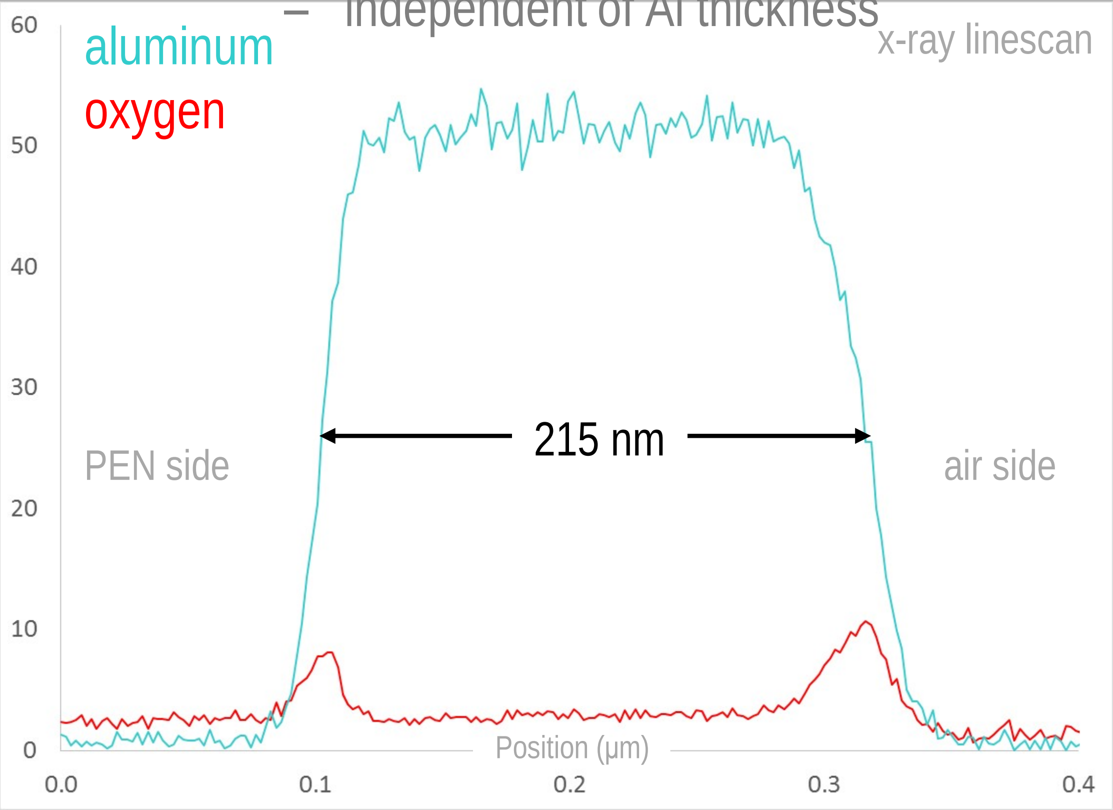
Bright aluminum
(gray aluminum)

- columnar microstructure
- Al grains, typically 50 nm wide, growing through the full thickness of the film.
- thin oxide at each surface
- similar to evaporated Al
  - 3 nm oxide on each surface
  - independent of Al thickness





Questions

1) How much contamination do I have?

and

2) How much is too much?

Contamination Amount

$$\frac{\text{Amount of contaminant } (H_2O)}{\text{Amount of intended material (Al)}}$$

Impingement rates of both

Impingement rate of aluminum
in a roll coater

$$I\ [\text{atoms/cm}^2/\text{sec}] = \frac{\text{Thick[nm]} \times (\text{Density/AtomicWt}) \times \text{Speed[ft/min]} \times 10^{15}}{\text{CoatingApertureWidth[ft]}}$$

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For aluminum [Density/AtomicWt] = 0.1 moles/cm^3

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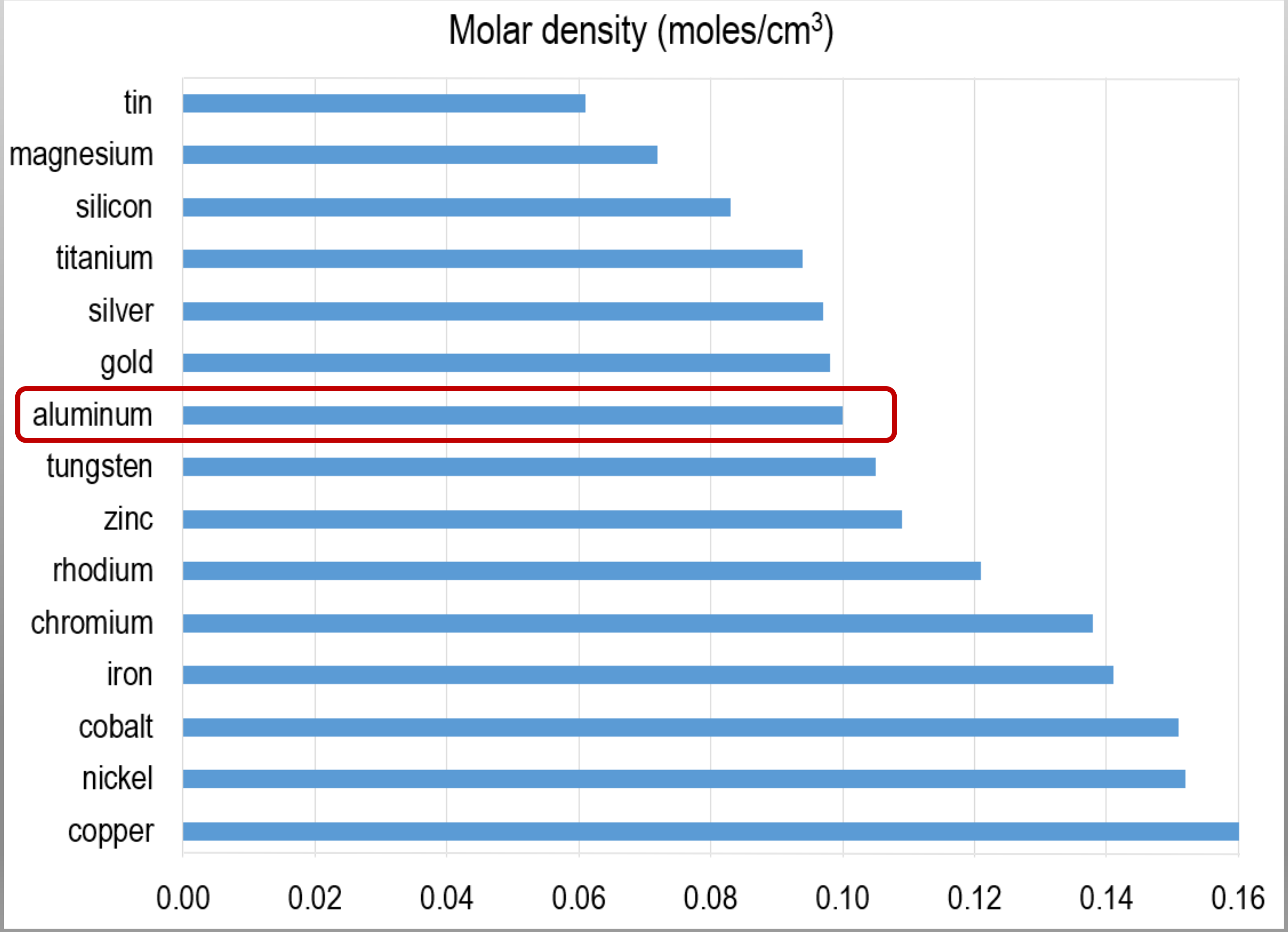
$$I\ [\text{atoms/nm}^2/\text{sec}] = \frac{\text{Thick[nm] x Speed[ft/min]}}{\text{CoatingApertureWidth[ft]}} = \frac{\text{Thick[nm] x Speed[m/min]}}{\text{CoatingApertureWidth[m]}}$$

Density (g/cm^3) / Atomic Weight (g/mole)



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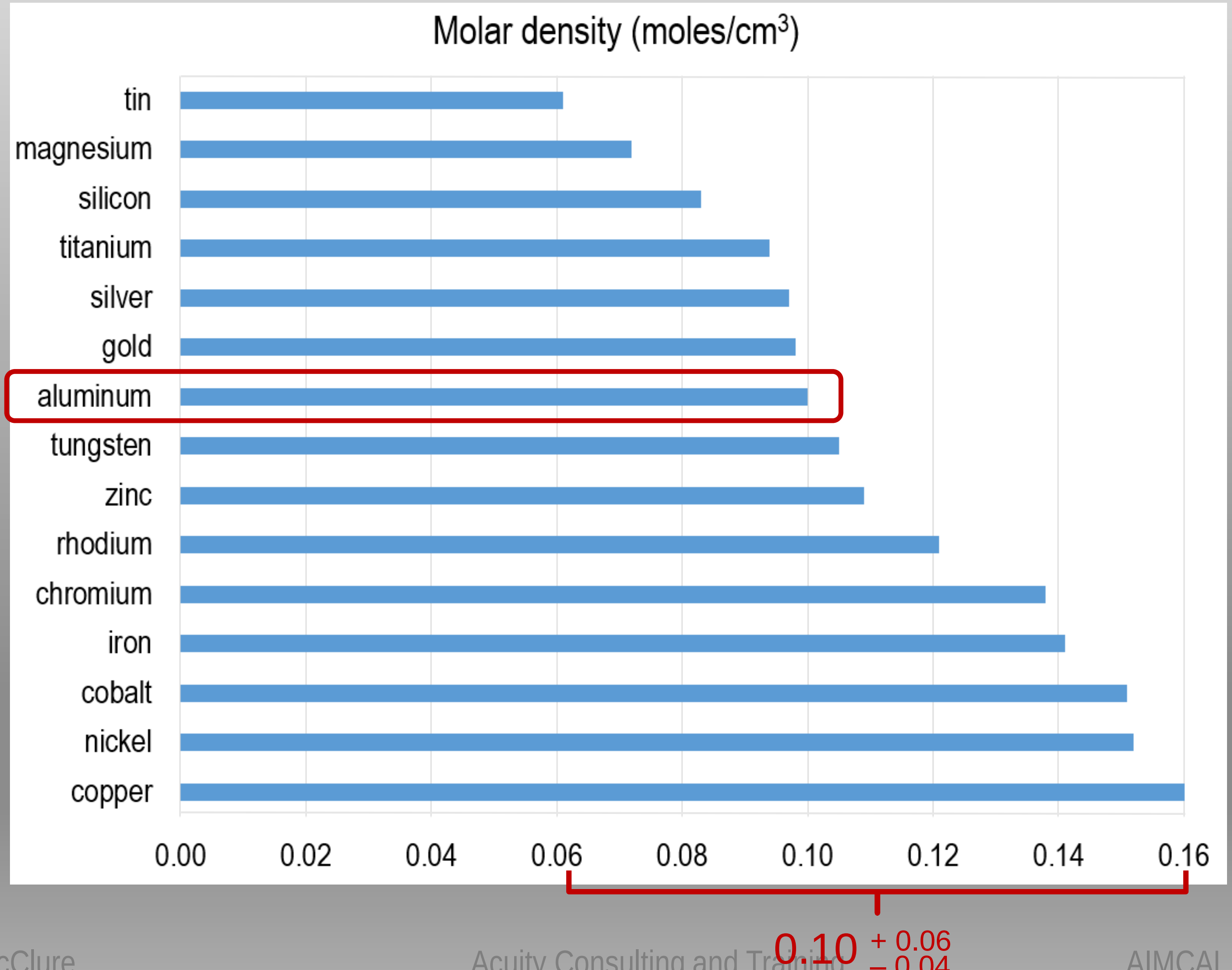

Background gas impingement rate

- It's all about the pressure

Background gas pressure

- Unless there’s a leak, or you add gas,

Background gas pressure

- Unless there's a leak, or you add gas,
  - it's all H_2O.

Background gas pressure

- Unless there's a leak, or you add gas,
  - it's all H_2O.

A residual gas analyzer

will confirm this.

Background gas pressure

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Background gas pressure

- Unless there's a leak, or you add gas,
  - it's all H_2O.
- Atmospheric gasses are "all" pumped away while pumping down to vacuum.
- H_2O comes from substrate outgassing.
- H_2O comes from desorption from internal surfaces.

Time constant for outgassing and desorption can be minutes to hours, even with heating.

How much H_2O hits my substrate

- The rate of gas molecules hitting ALL surfaces in our chambers is called:
  - the impingement rate = I
- I [molecules/cm^2/sec] = 3.8 x 10^{20} x P [Torr]
- At 10^{-4} Torr,

I = 4 x 10^{16} molecules/cm^2/sec

= 4 x 10^2 molecules/nm^2/sec

= 400 molecules/nm^2/sec

How much contamination do I have?

H_2O hitting my substrate:

at 10^{-4} Torr $I = 400$ molecules/nm^2/sec

Al hitting my substrate:

$$I\ [\text{atoms/nm}^2/\text{sec}] = \frac{\text{Thick[nm]} \times \text{Speed[ft/min]}}{\text{CoatingApertureWidth[ft]}}$$

40 nm * 1000 fpm / 1 ft wide aperture

$I = 40{,}000$ atoms/nm^2/sec

Ratio (H_2O / Al) = 400 / 40,000 = 1:100

How much H_2O is too much?

- At 10^{-4} Torr

$$I = 400 \text{ molecules/nm}^2\text{/sec}$$

- At 10^{-6} Torr

$$I = 4 \text{ molecules/nm}^2\text{/sec}$$

Impingement rate sample

At 1×10^{-6} Torr, the water vapor impingement rate =

I = 4 molecules/nm^2-sec

For aluminum evaporation at 1 nm/sec, the Al atom impingement rate =

60 atoms/nm^2-sec

[16 atoms / nm^2 is a monolayer $\longrightarrow$ ~4 monolayers / sec]

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For aluminum evaporation at 0.7 nm/sec, the Al atom impingement rate =

42 atoms/nm^2-sec

A 6 nm film is conducting: 55 Ω/□ and grey in color.

Impingement rates ratio: water molecules / Al atoms = 4 / 42 = 1:10

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For aluminum evaporation at 0.2 nm/sec, the Al atom impingement rate =

12 atoms/nm^2-sec

A 6 nm film is insulating: > 2000 $\Omega/\square$ and brown in color

Impingement rates ratio: water molecules / Al atoms = 4 / 12 = 1:3

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Recap

- Metallic aluminum films for

  water molecules / Al atoms = 1:10

- Insulating aluminum oxide films for

  water molecules / Al atoms = 1:3

- Not <u>precise</u> bounds but reasonably narrow.

Beware . . .

All this discussion and the math is based on averages and the assumption of both uniform and equilibrium conditions.

Beware . . .

1. Our coatings are seldom uniform over the coating aperture; typically the rate at the leading and trailing edges is (much) lower than that at the center; thus those areas are more susceptible to contamination.
2. Getter pumping by evaporated atoms in the deposition zone reduces the local background gas pressure, with the result that the gauge at the chamber wall may not reflect the pressure in the deposition zone.

Beware . . .

3. In high rate evaporation the local density of aluminum atoms forms a region of (much) higher pressure and lower mean free path. The pressure of the Al flux may sweep out water molecules and prevent the migration of water molecules into the coating zone
4. In high rate <u>sputtering</u> the energy from the sputter source heats the gas above the source and may (dramatically) reduce the local gas density.

If we coat fast enough . . .

we could eliminate contamination at still higher pressures!

Can we coat at 10-3 or even 10-2 Torr?

If we coat fast enough . . .

Can we coat at 10-3 or even 10-2 Torr?

We now have to think about the mean free path:

λ = 500 mm at 10^{-4} Torr

= 50 mm at 10^{-3} Torr

= 5 mm at 10^{-2} Torr

Scattering of the Al atoms becomes problematic!

Comments !

Questions ?