A Novel Instrument for the In-Situ Measurement of the Stress in Thin Films

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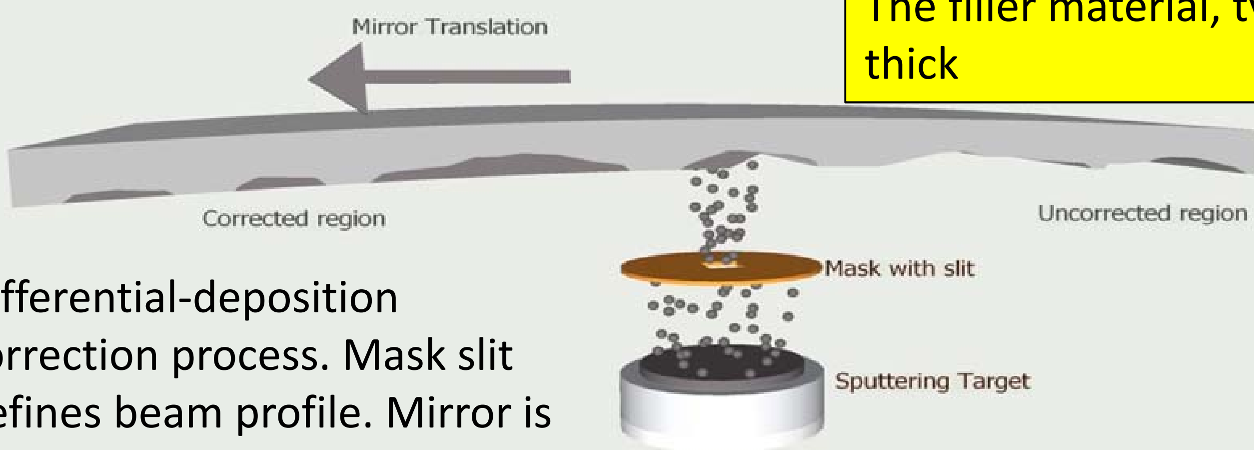
Motivation: Figure correction nickel replicated X-ray optics

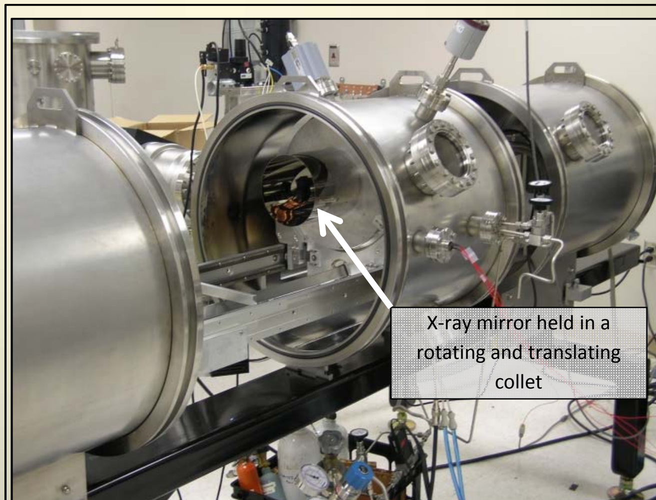
The filler material, typically 10s to 100s of nm thick



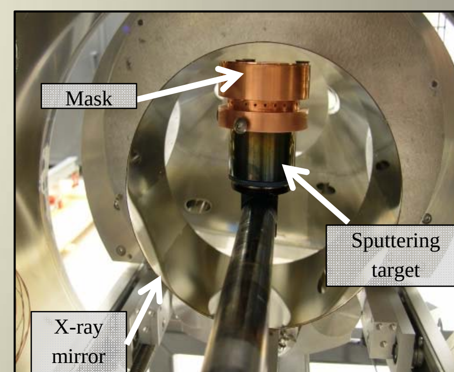
Differential-deposition correction process. Mask slit defines beam profile. Mirror is translated over slit at varying velocity to coat the desired figure-correcting profile.

The success of this technique requires the corrective layer to have low stress (<1 MPa) in some cases.

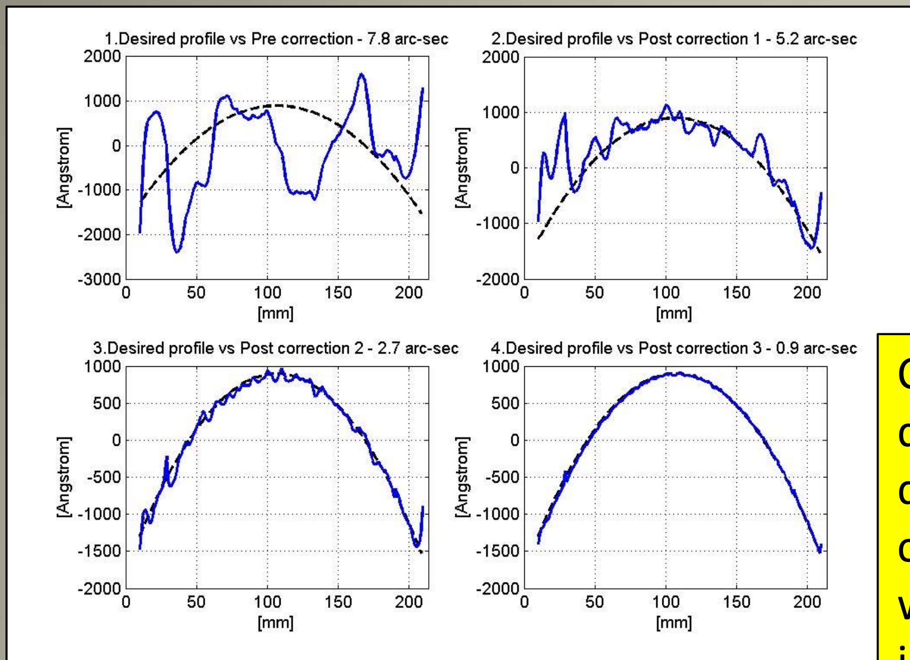
The stress in the nickel filler layer could be “tuned” to low stress values in-situ by varying gas pressure and/or cathode power.



Horizontal differential-deposition chamber

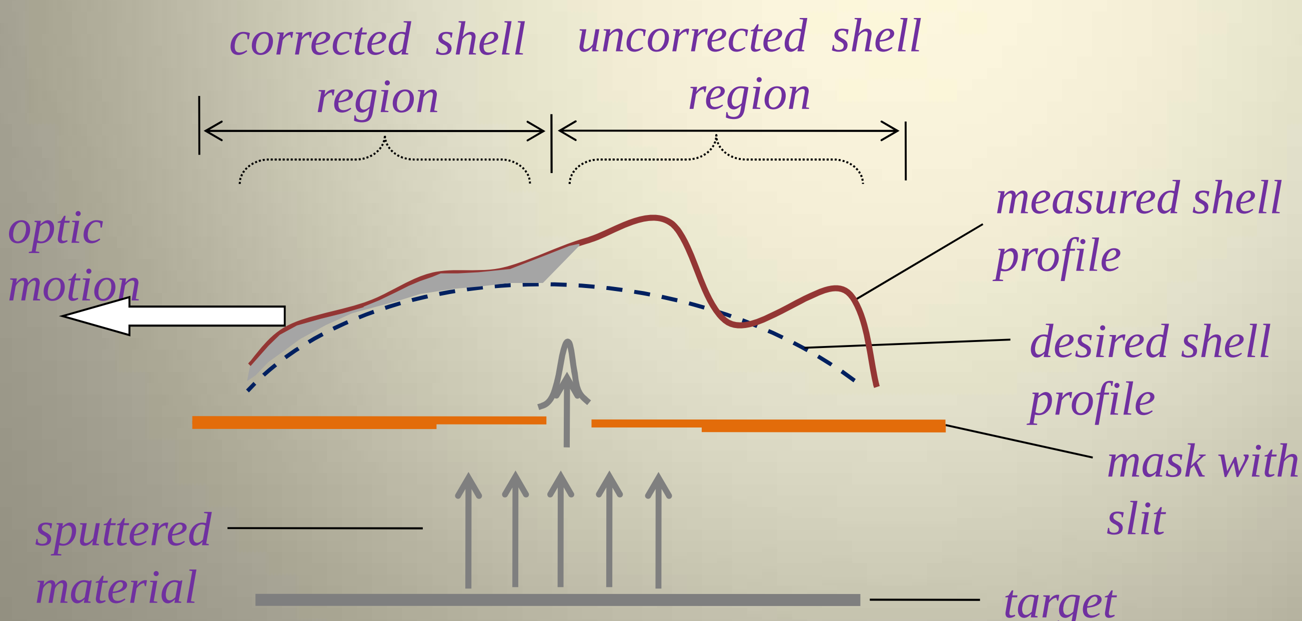


Sputtering head with copper mask positioned inside shell



Simulated correction sequence showing parabolic axial figure profile before (top left) and after 3 stages of correction using a beam of FWHM = 14mm, 5.2 mm and 1.7 mm respectively. The dotted line gives the desired figure and the solid line gives the figure obtained at each stage.

Clearly stress is a major concern in the differential deposition process. If the filler deposit is highly stressed, then the corrective coating can itself distort the mirror and it would be hard to converge to significantly improved angular resolution

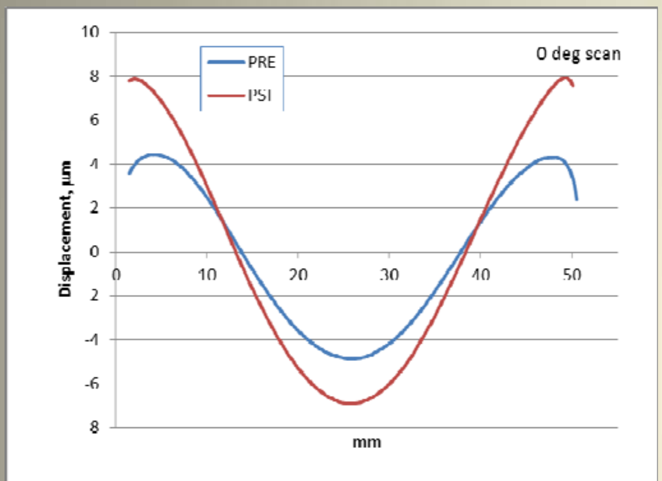


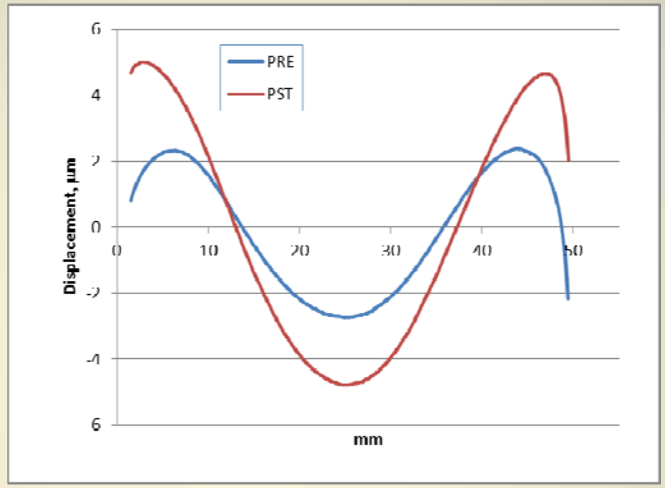
In-Situ Methodology

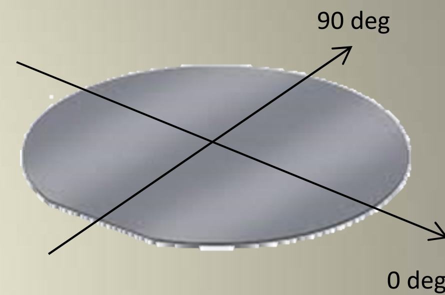
Deformation Mode:

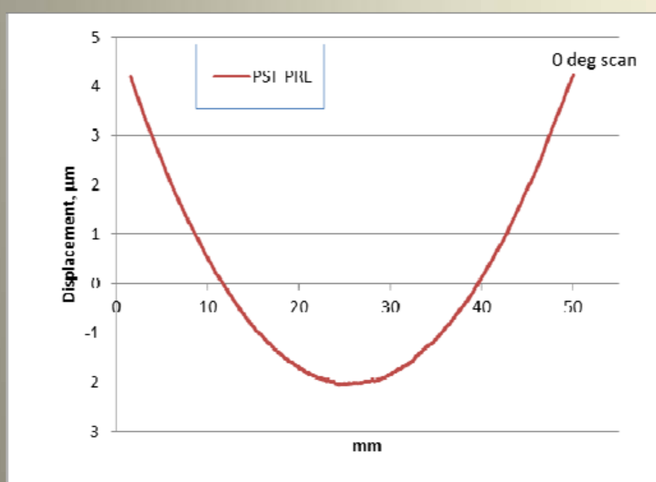
$$A = \sigma h_f \frac{D_s^2}{h_s^3}$$

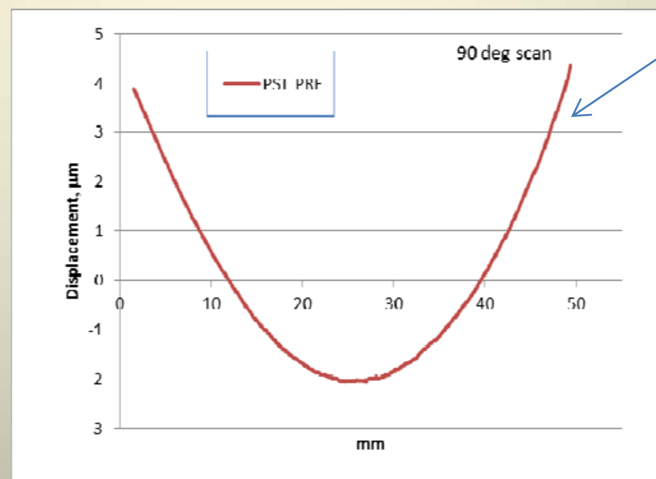
The substrate deformation will be spherical provided $A \leq 0.2\, A_c$ is satisfied (for a silicon substrate A_c = 680 GPa).
This condition can always be satisfied for different stress regimes by changing the substrate thickness, h_s, or diameter D_s as necessary.











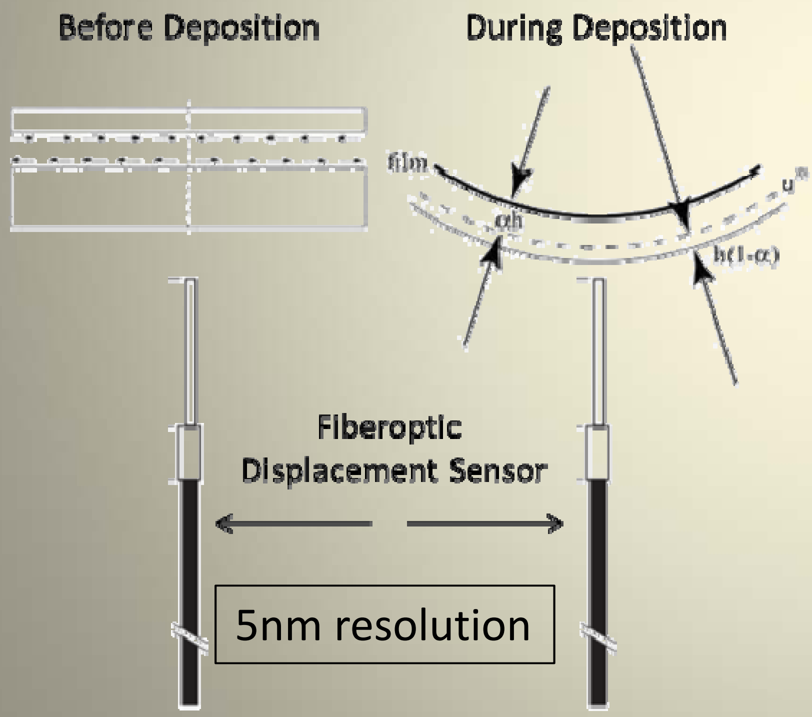
$$k \approx \frac{d^2 z}{d^2 x} = const$$

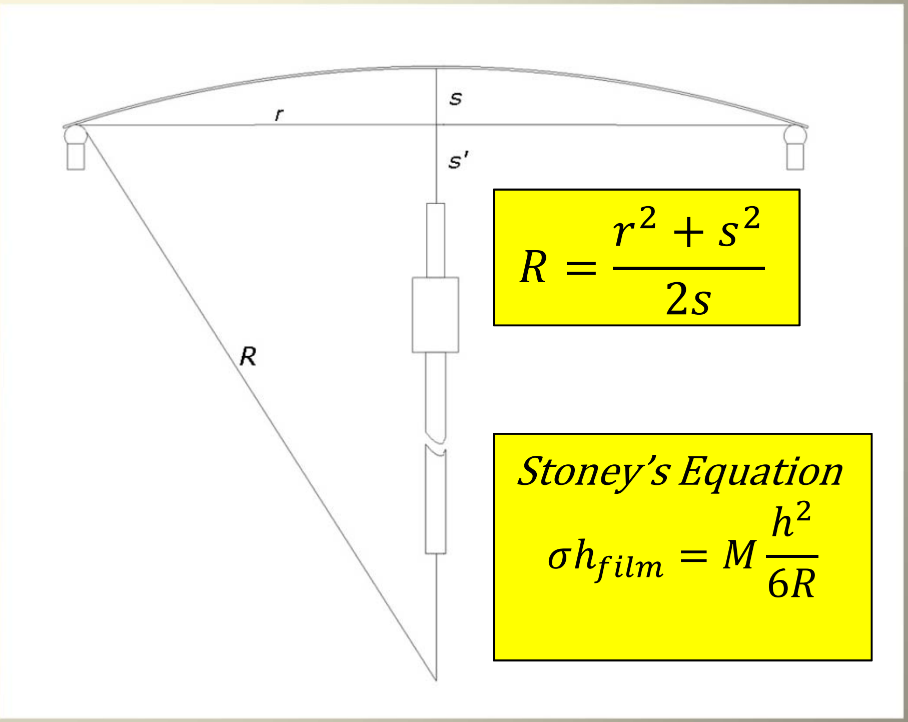
R_0=47.2m R_{90}=46.7

Since substrate deformation is know to be spherical it is only necessary to measure the sagittal, s, to infer its curvature from which the Stoney equation can be employed.

This measurement is performed during deposition by measuring the backside of a double side polished substrate with a non-contact variation of the classic spherometer.

The sensor can measure displacements with a resolution of 5nm.



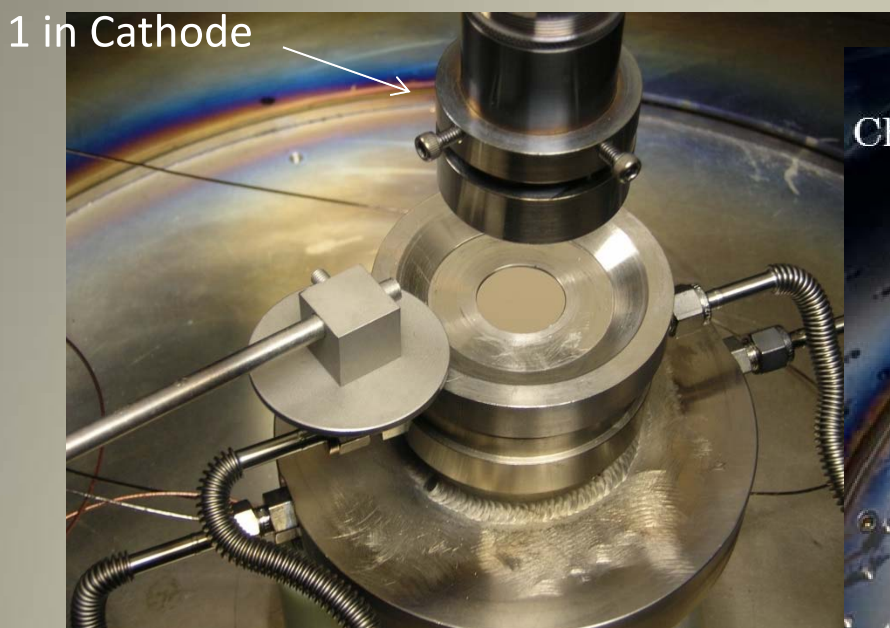


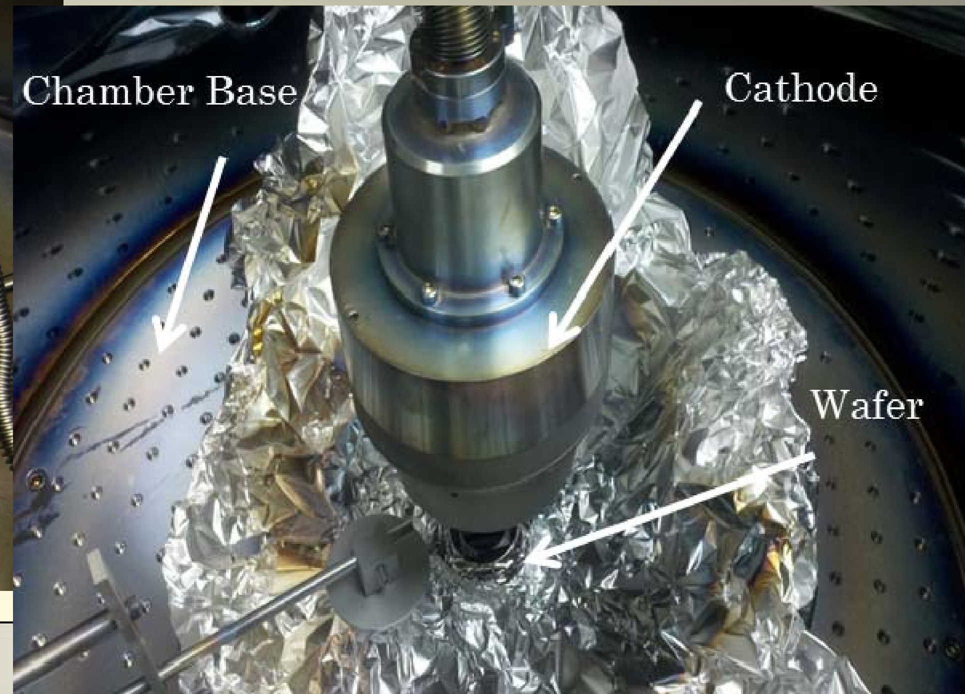
$$R = \frac{r^2 + s^2}{2s}$$

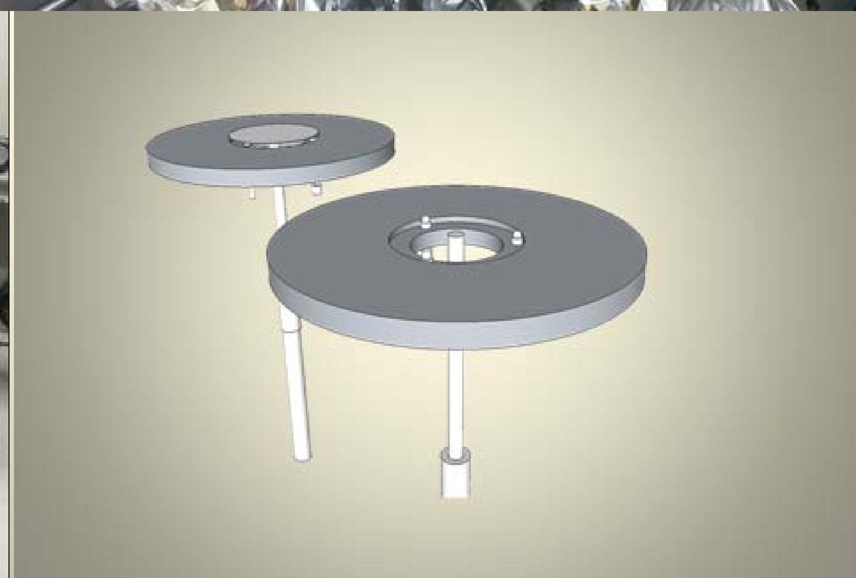
Stoney's Equation

$$\sigma h_{film} = M \frac{h^2}{6R}$$

Patent Pending

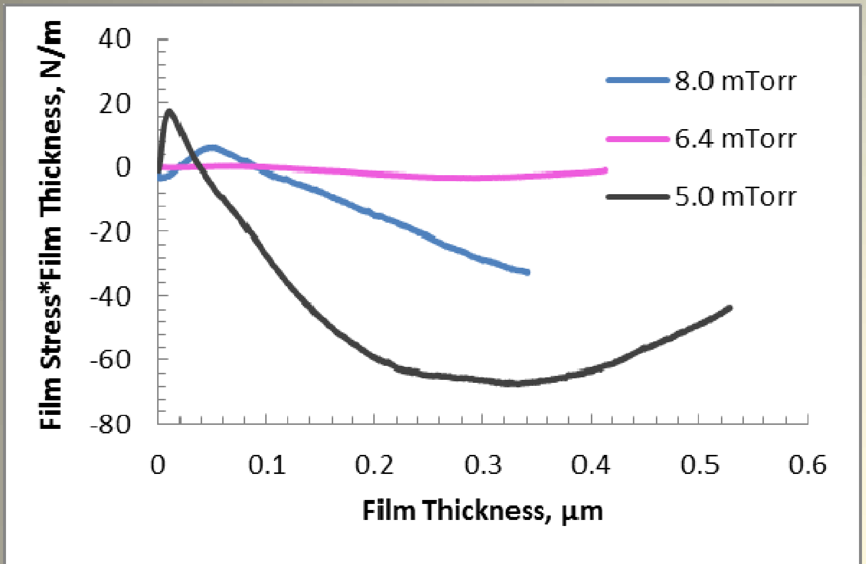


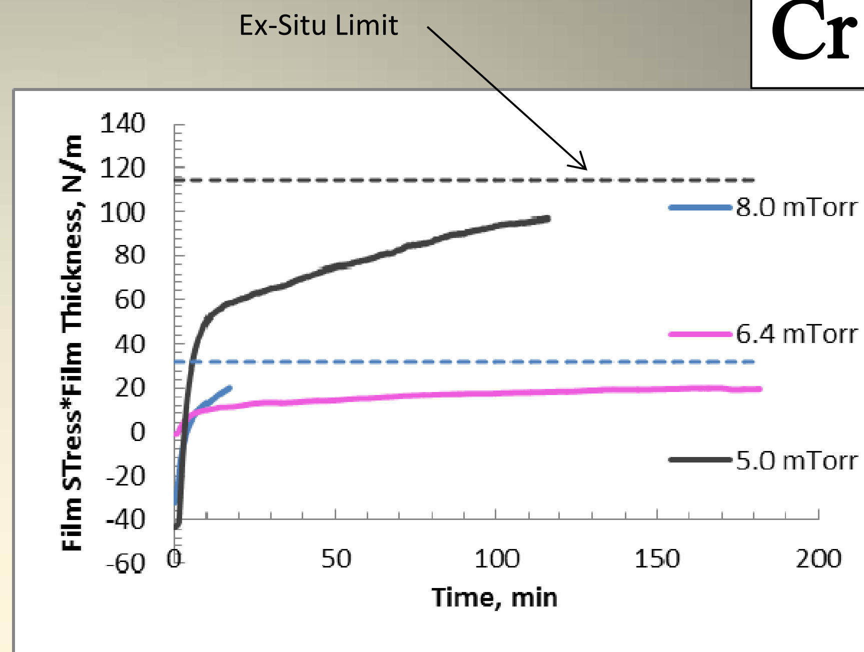




Cr

Early Results: 3 in circular cathode





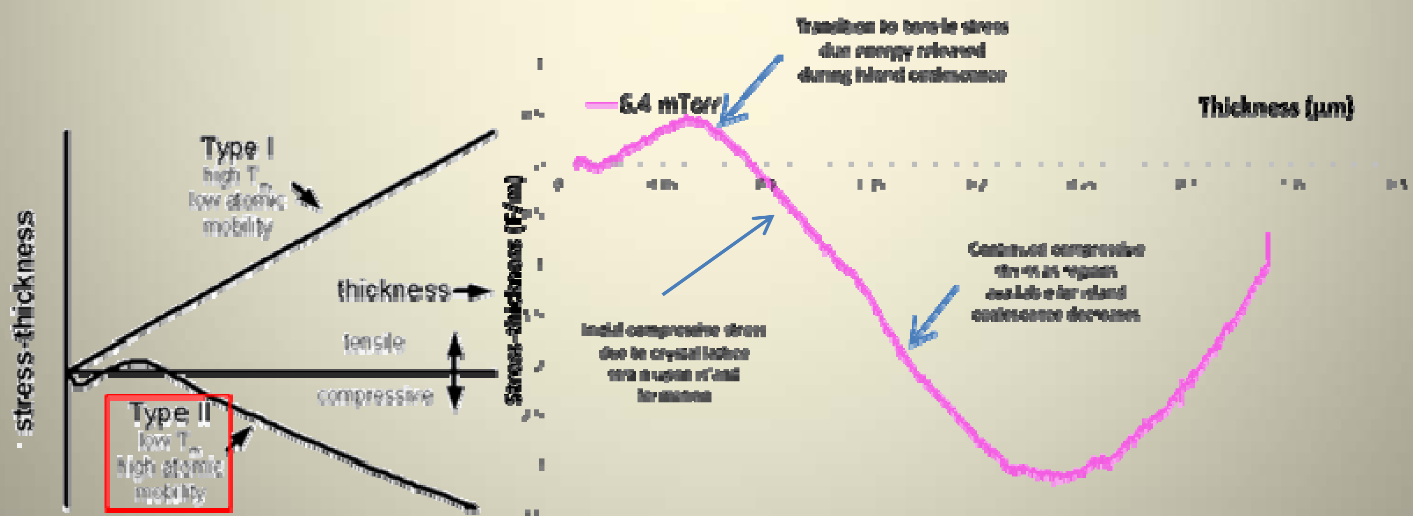
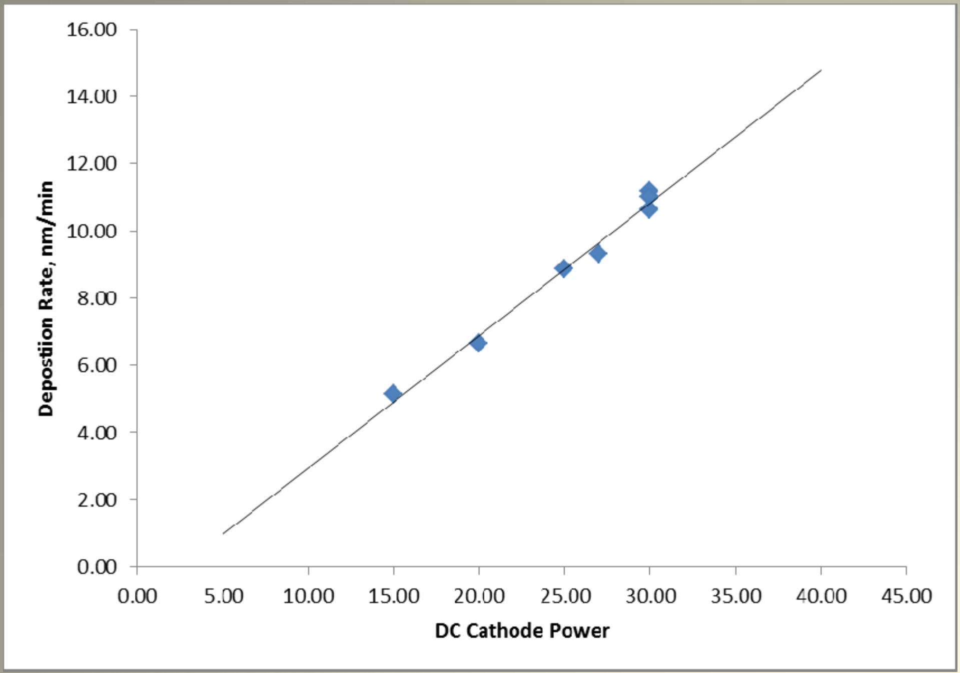
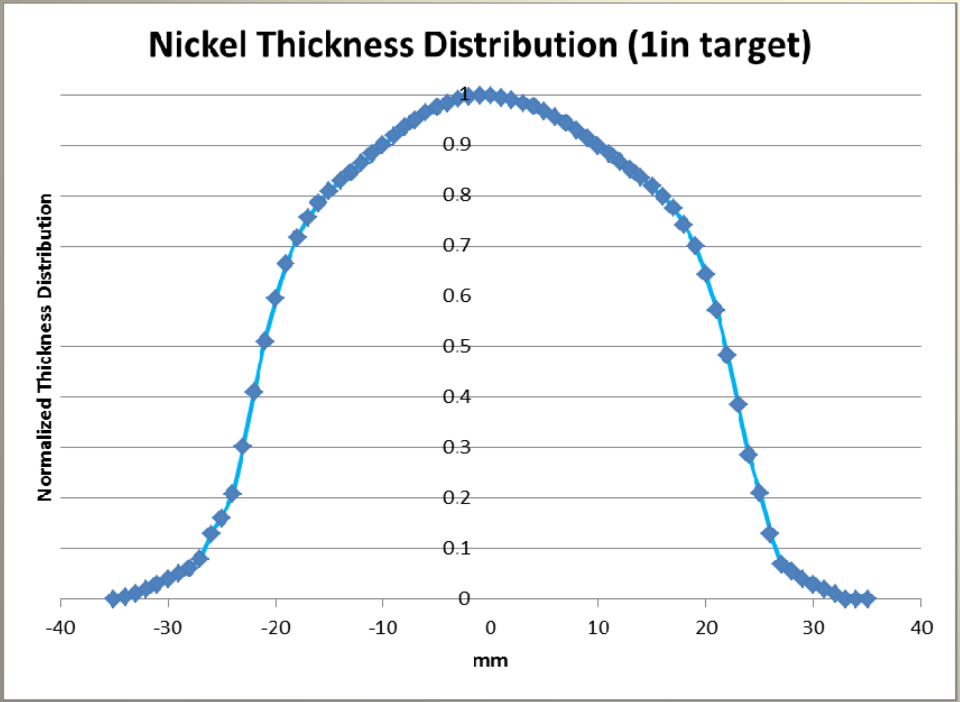


Figure 1- After R. Abermann, Vacuum 41, 1279 (1990) (left); Measured In-Situ (right)- Data matches measured curves from several published experiments.





The thickness distribution on 1 in. substrate From the 1 in. target is >10% (outside of the Stoney regime).

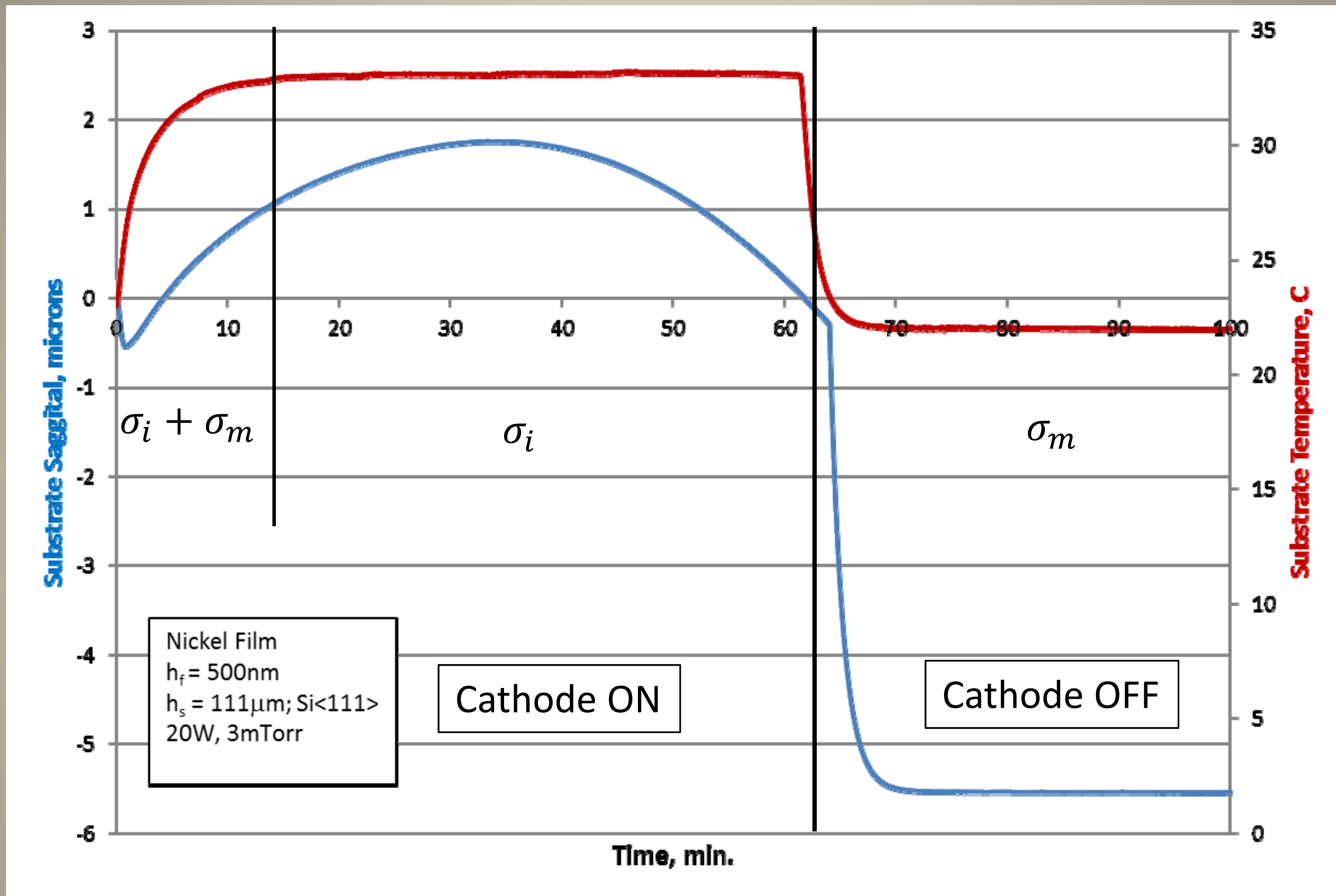
In practice the stress will be "tuned" to zero using gas pressure or cathode power. Zero displacement should result in zero stress regardless of the thickness distribution.

Further, azimuthal symmetry should still result in a spherical deformation but give large errors in stress when employing the Stoney formalism.

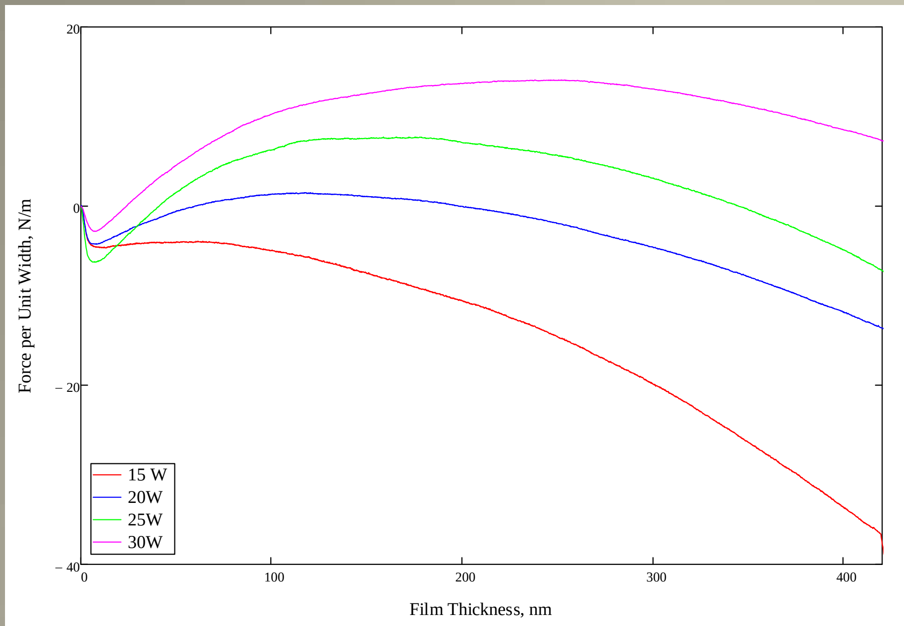
For the results that follow we are interested in relative changes in stress.

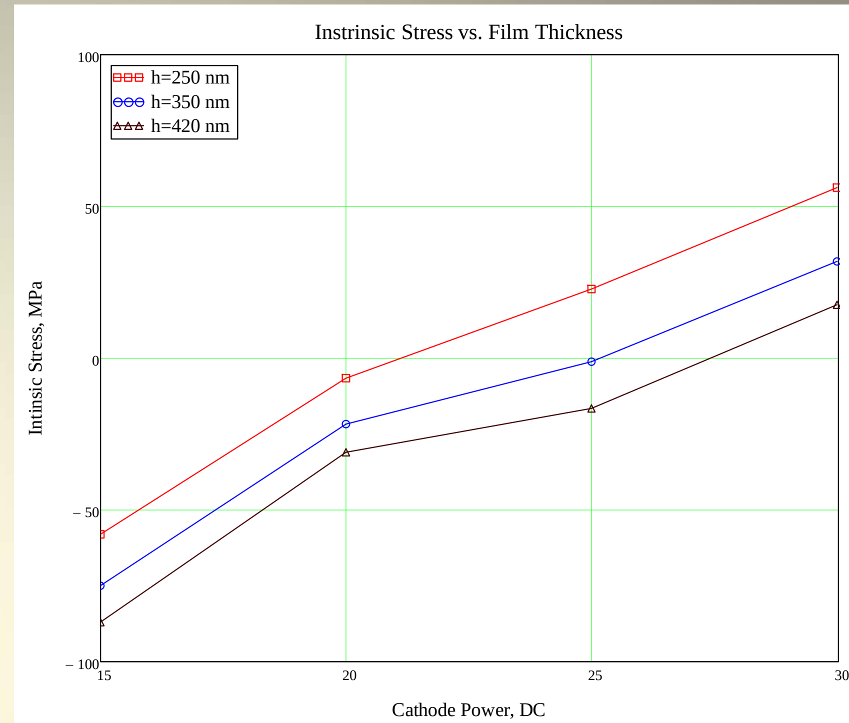
Future work will include repeating these results utilizing a 3 in. cathode.

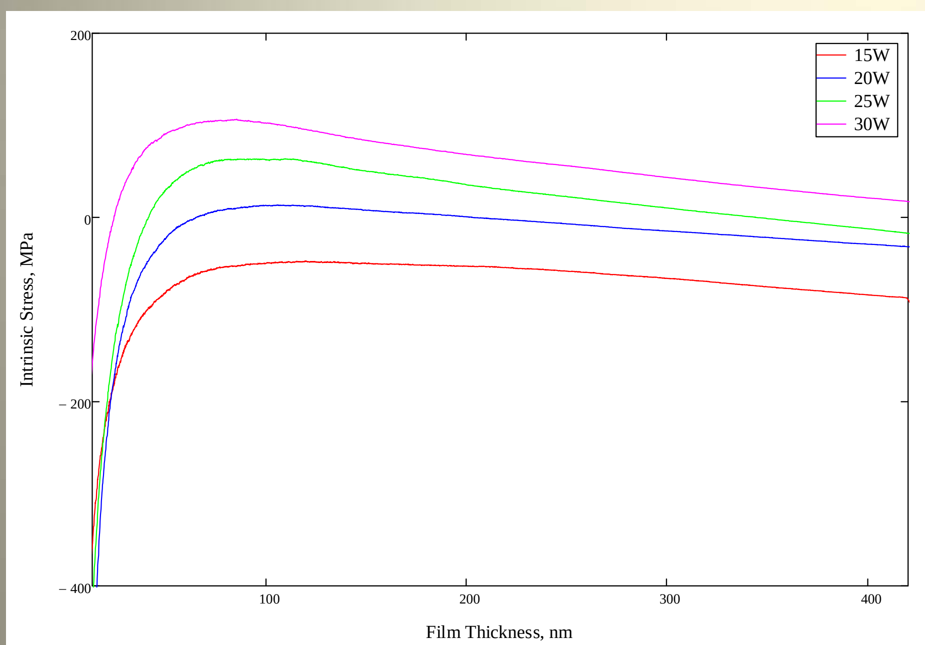
Deposition rate is assumed constant throughout film growth.



Substrate Saggital, microns
Substrate Temperature, C
Time, min.
$\sigma_i + \sigma_m$
σ_i
σ_m
Nickel Film
h_f = 500nm
h_s = 111µm; Si<111>
20W, 3mTorr
Cathode ON
Cathode OFF



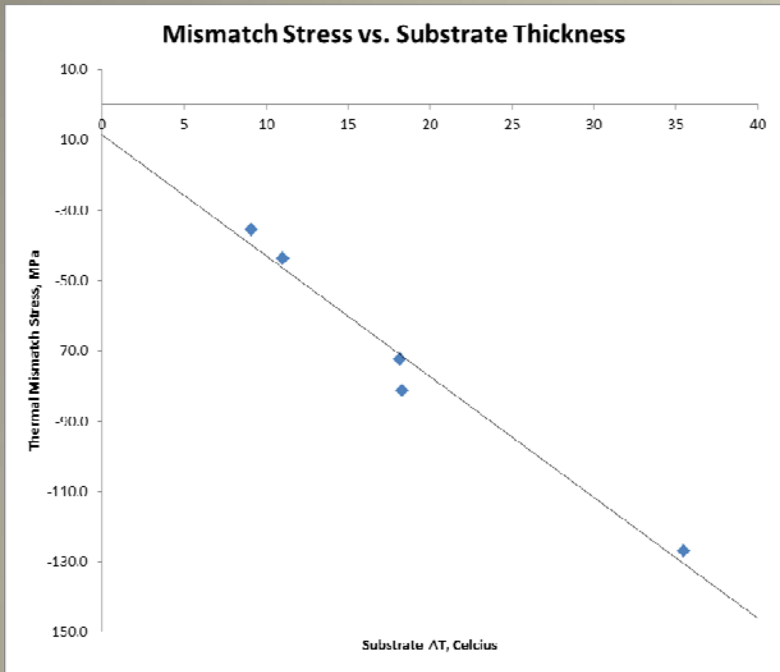




Fixed Ar Pressure: 3mTorr

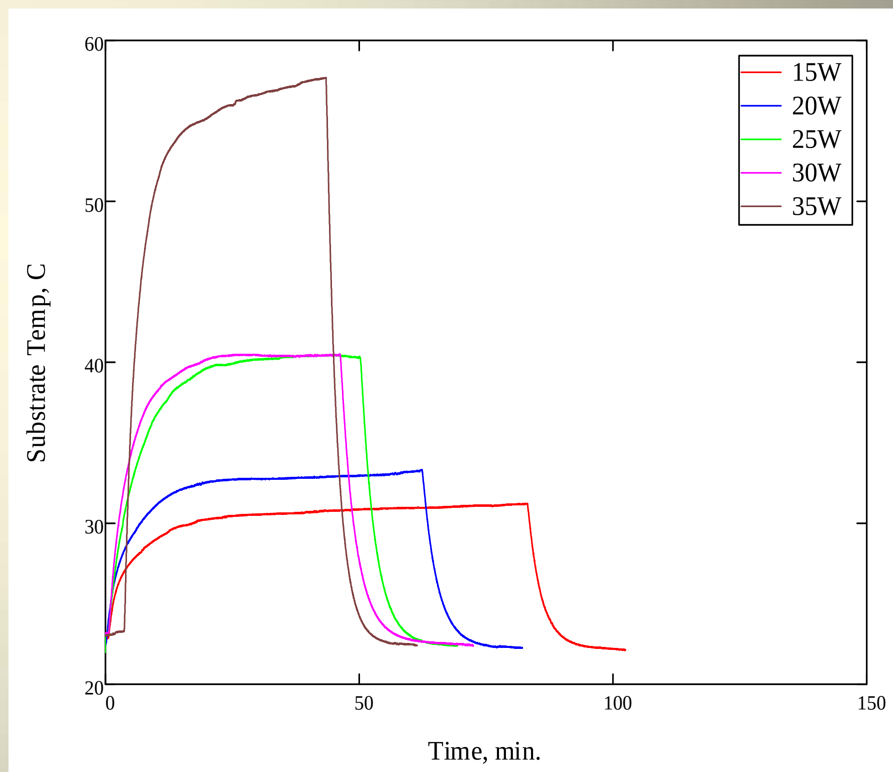
DC, W	σ_i, MPa	h_f, nm	σ_i, MPa	h_f, nm	σ_i, MPa	h_f, nm
15	-58	250	-75	350	-87	420
20	-7		-22		-31	
25	23		-1		-17	
30	56		32		18	

280 µm substrate, Si <111>



$$\sigma_{Tot} = \sigma_i + \sigma_m$$

$$\sigma_m = M_f(\alpha_s - \alpha_f)\Delta T$$

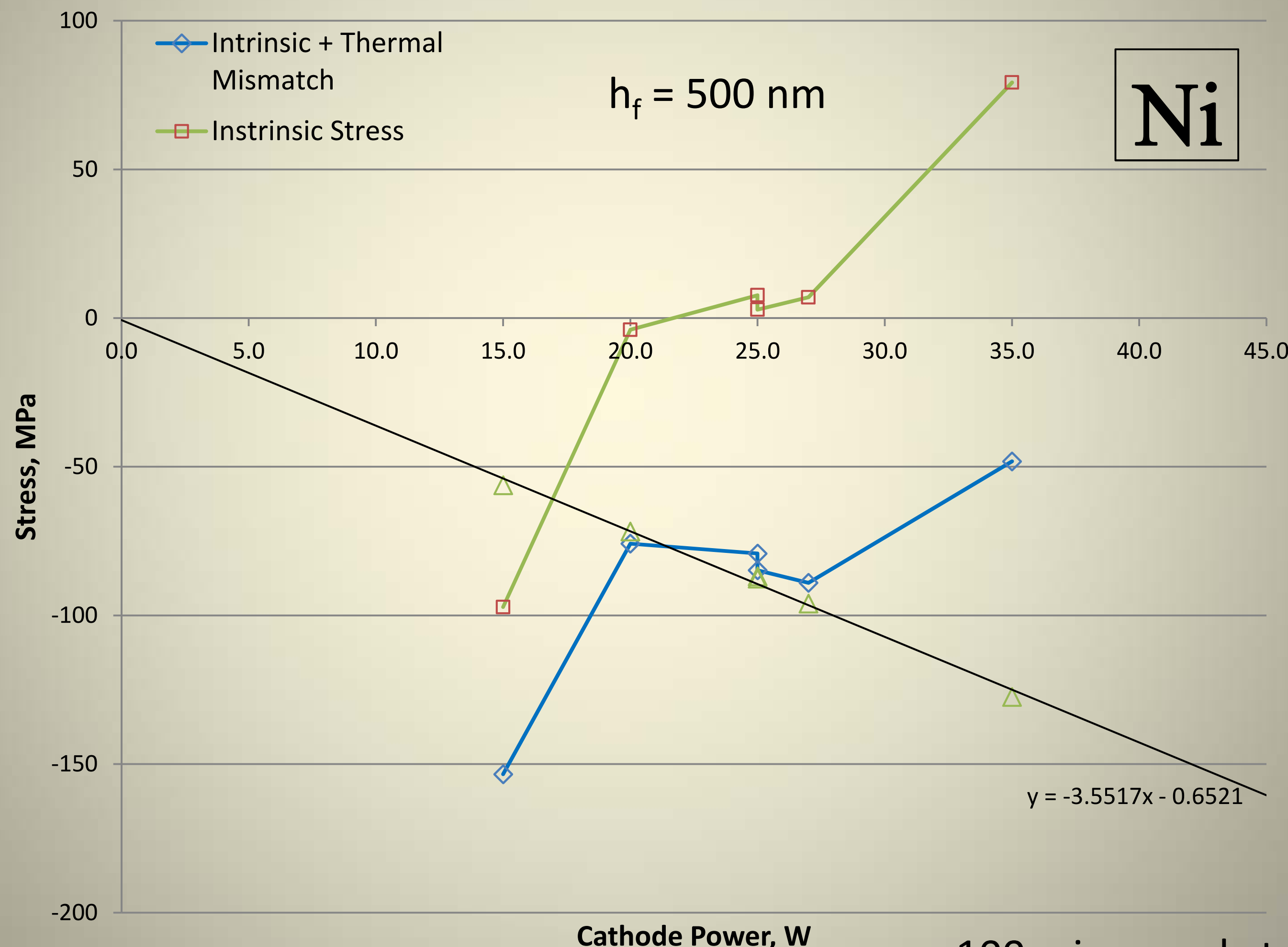


The measured mismatch stress agrees reasonably well to the calculated value using bulk constants .

There can be some inconsistent temperature measurements such as at 30W possibly due to variation in thermal contact.

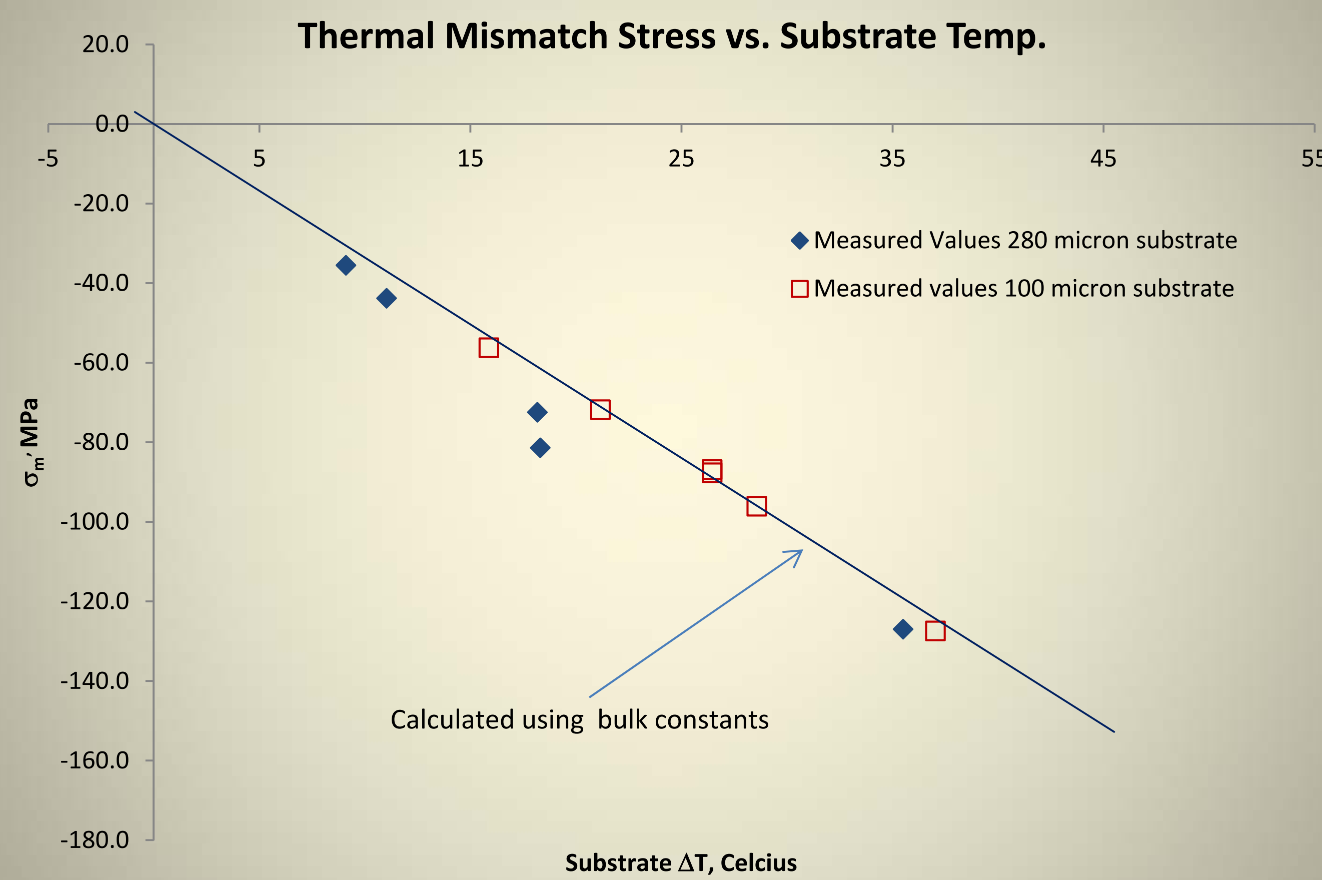
280 μm substrate thickness

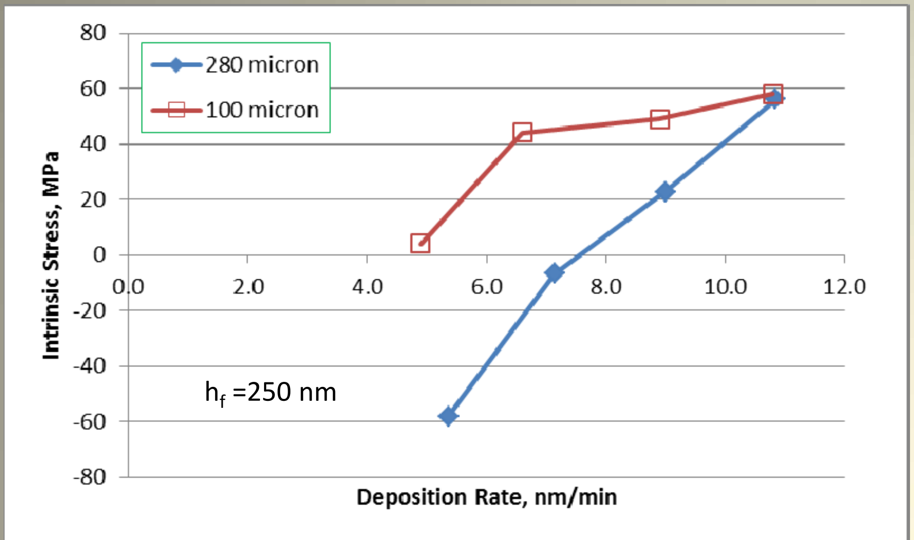
In addition to the high resolution of the sensor, the sensitivity can be further enhanced by utilized ever thinner substrates.

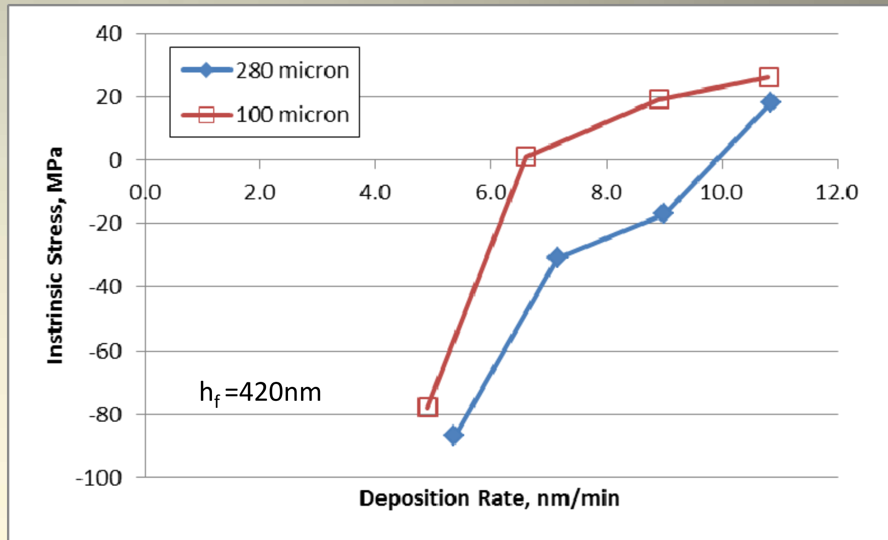


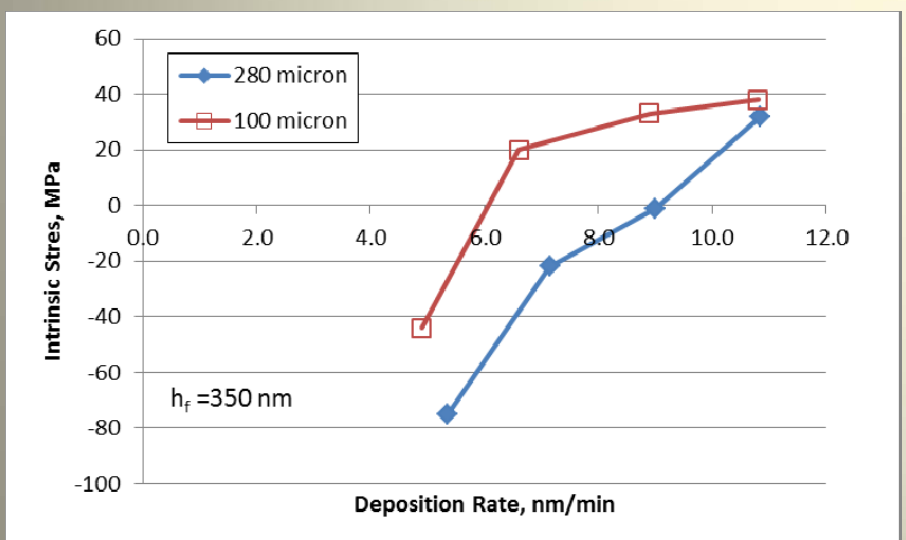
100 micron substrate

Thermal Mismatch Stress Comparison for 280 and 100 micron thick Si substrates









DC, W	σ_i, MPa	h_f, nm	σ_i, MPa	h_f, nm	σ_i, MPa	h_f, nm	ξ, nm/s	h_s, µm
15	-58	250	-75	350	-87	420	5.4	250
20	-7		-22		-31		7.1	
25	23		-1		-17		9.0	
30	56		32		18		10.9	
15	4		-44		-78		4.9	111
20	44		20		1		6.6	
25	49		33		19		8.9	
30	58		38		26		10.8	

Intrinsic Stress Comparison with substrate thickness 100 & 280 microns

Discussion

Comparison of the same film on different thickness substrates should result in similar stress values.

We see reasonably good agreement between 100 and 280 micron substrate thickness when considering the stress due to thermal mismatch in nickel films. The agreement when comparing the intrinsic stress is unacceptably worse.

Utilization of the 1 in. cathode is not ideal for these experiments due to the strong non uniformity of film thickness on the 1 in. substrate. Apart from deviating from the assumptions of uniform film thickness needed for accurate use of the Stoney formalism, the large thickness gradient is problematic since it requires highly repeatable positioning of the cathode after target changes, for example.

The target was changed between the sets of experiments utilizing different substrate thickness.

Differences in the thickness distribution on the substrate surface can result in differences in the measured stress values between the two ensembles of measurements.

Future work entails repeating this work with a 3 in. cathode which will result in nearly uniform film thickness on the 1 in. substrate.

Conclusions

This methodology seems to hold promise for the in-situ measurement of film stress.

The methodology holds particular promise when the goal is to tune the stress to zero by using gas pressure or cathode power. Near zero stress is critical consideration in the differential deposition process since the stress in the filler layer would affect the convergence of the process. The film distribution need not be uniform for this application since zero stress results in zero wafer displacement.

Since this method is contact free, very thin substrates can be used to increase the sensitivity.

This method provides a more robust alternative to other methods such as micro-cantilever with potentially comparable sensitivity—particularly when utilizing thin substrates (<100 microns). This allows in-situ measurement to be performed on larger substrates which facilitate other post deposition measurements that might be correlated to film stress such as surface roughness, or X-ray reflectivity.

Backside measurement of a double side polished wafer is utilized which avoids reflected interference effects which would otherwise results in loss of signal when other techniques such as mutli-beam or micro-cantilever techniques utilizing coherent light are used.