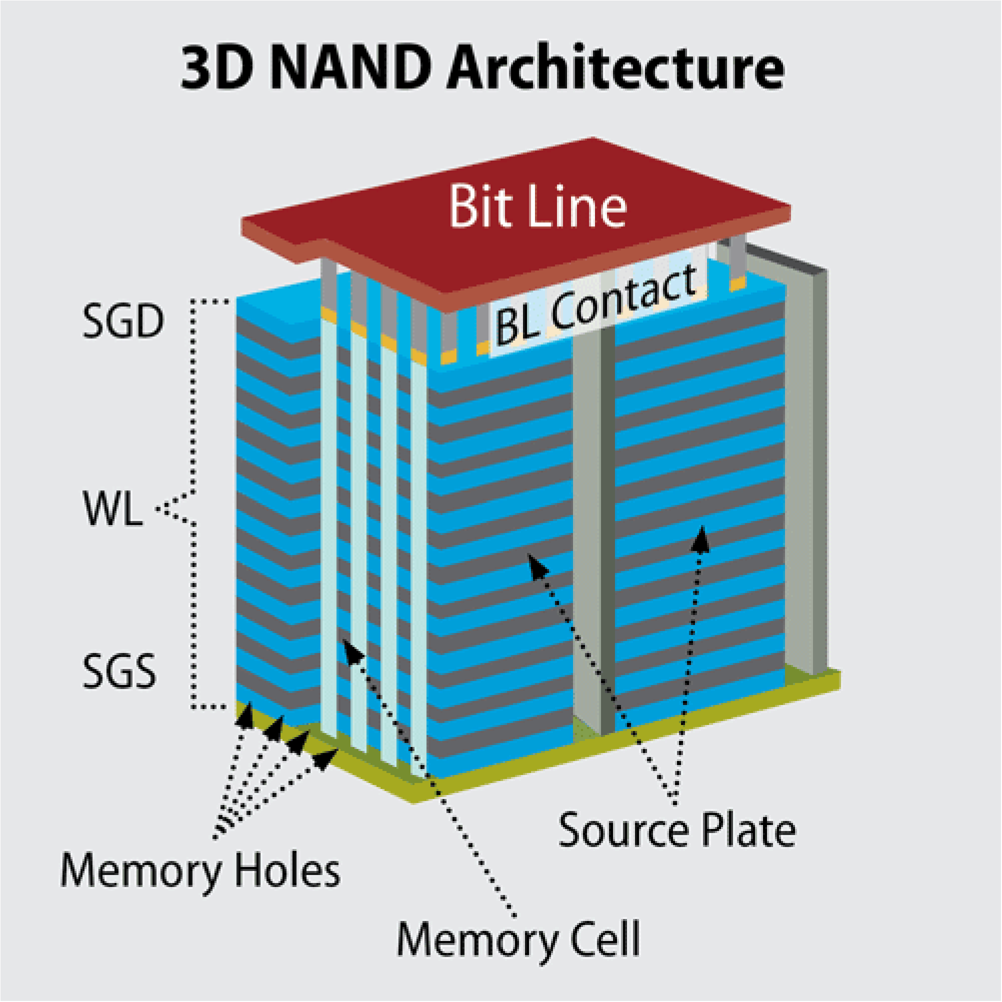
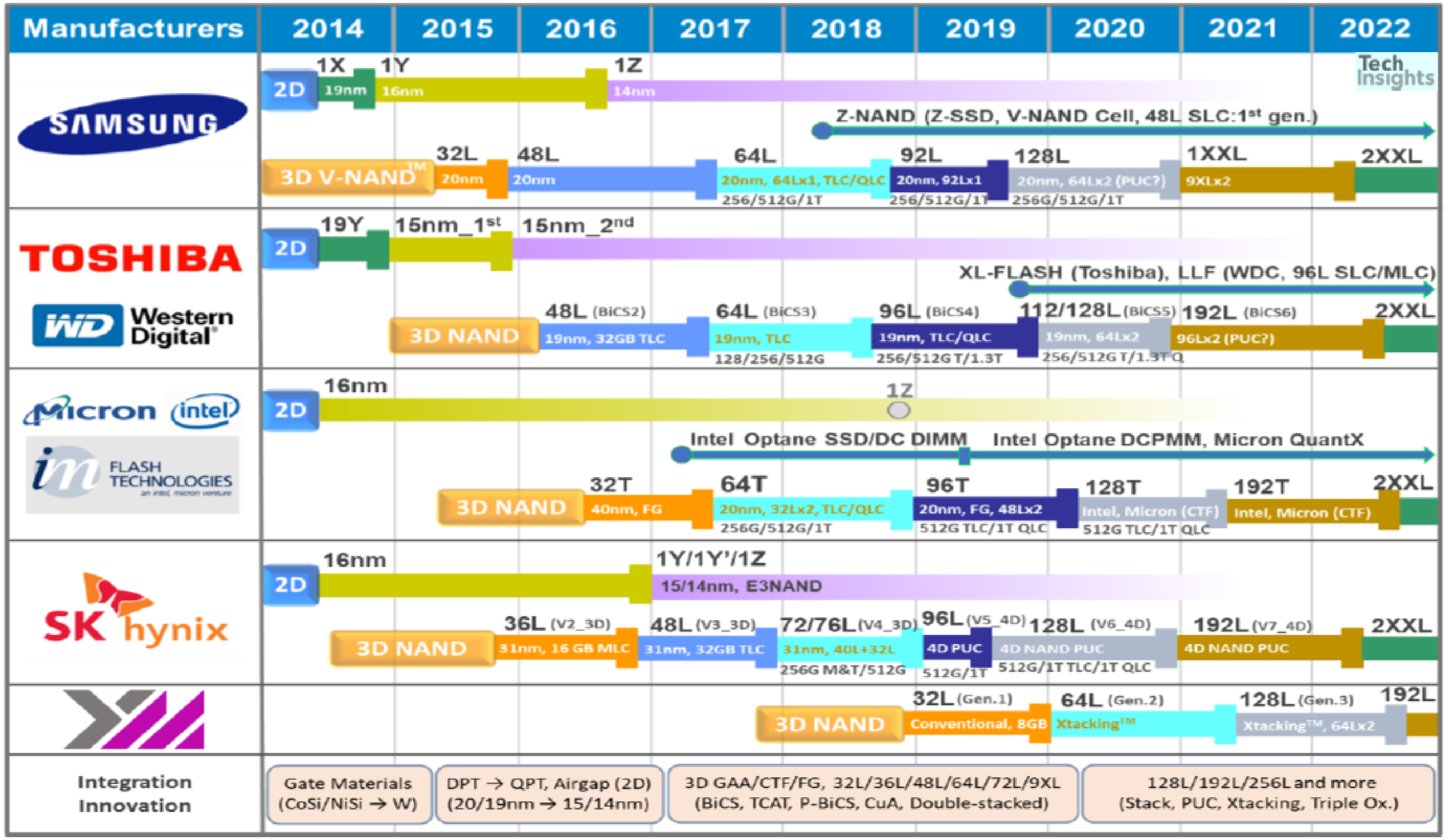
SMC STRATEGIC MATERIALS CONFERENCE

Alpha Carbon Hardmask in 3D-Nand Device Manufacturing Characterization by Multiple Metrology Methods for In-Line Control of High Aspect Ratio Etching

Priya Mukundhan, Ph.D. Thin Films Metrology

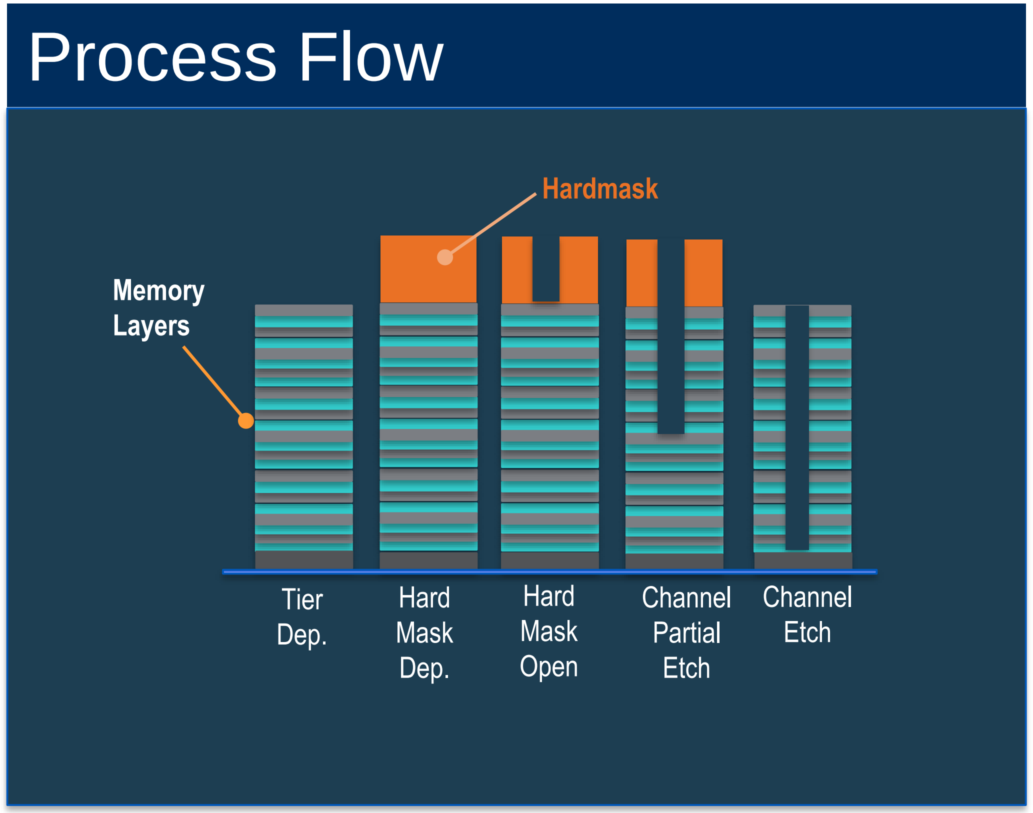
3D NAND Industry Roadmap

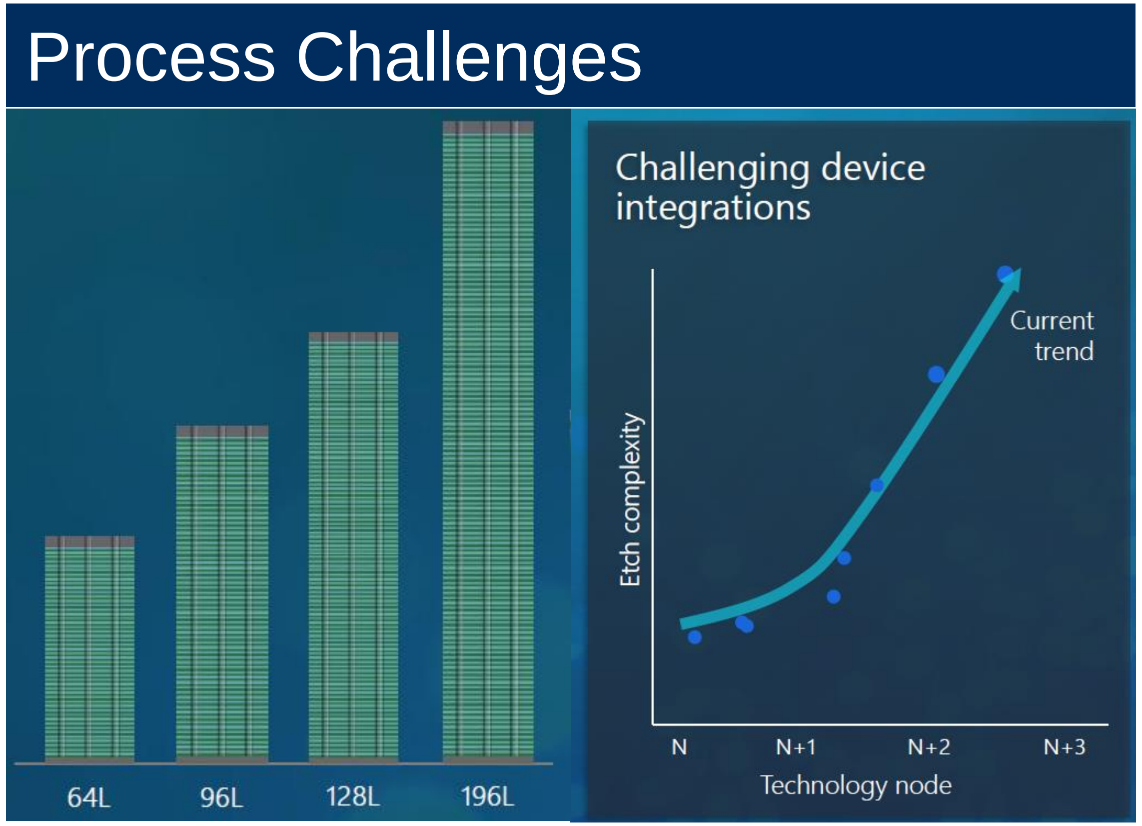




Source: Semiengineering.com, Tech Insights

3D NAND Etch Complexity





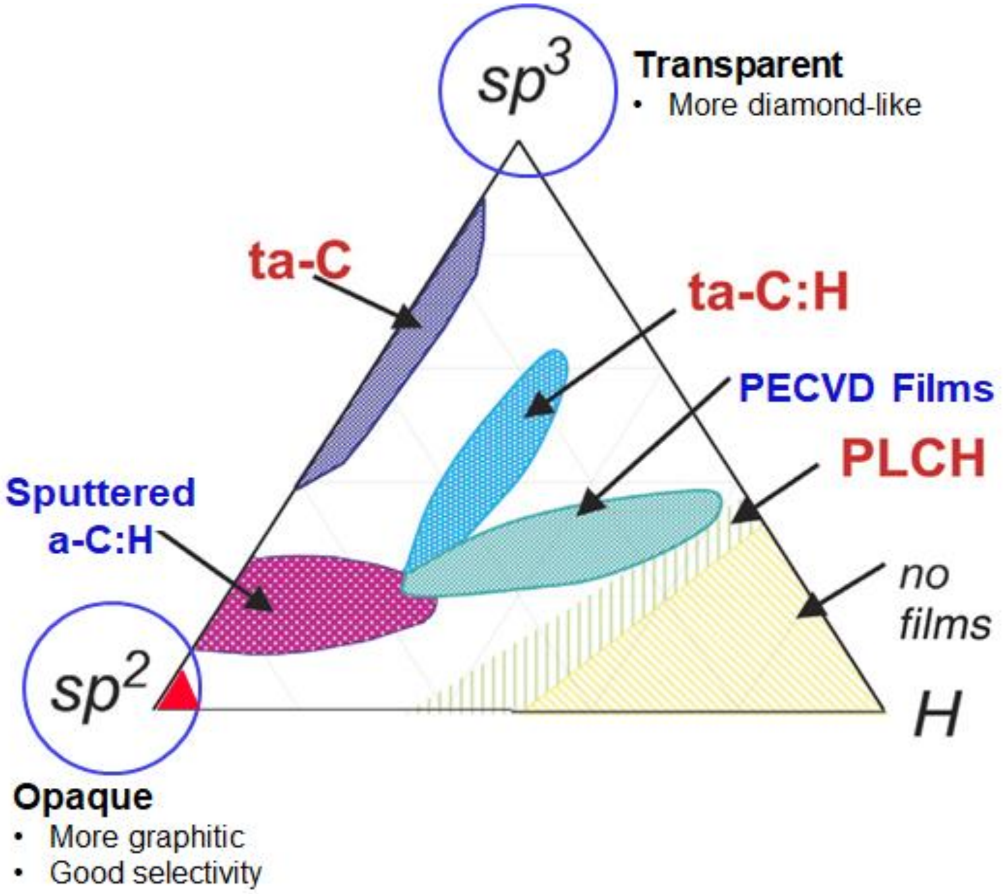
Hard mask material property & thickness critical for defining memory channel. Material should be

- highly etch selective and should have higher modulus
- as an etch hard mask, the film must block the F atoms from diffusing into sub-layers of the 3D NAND stack

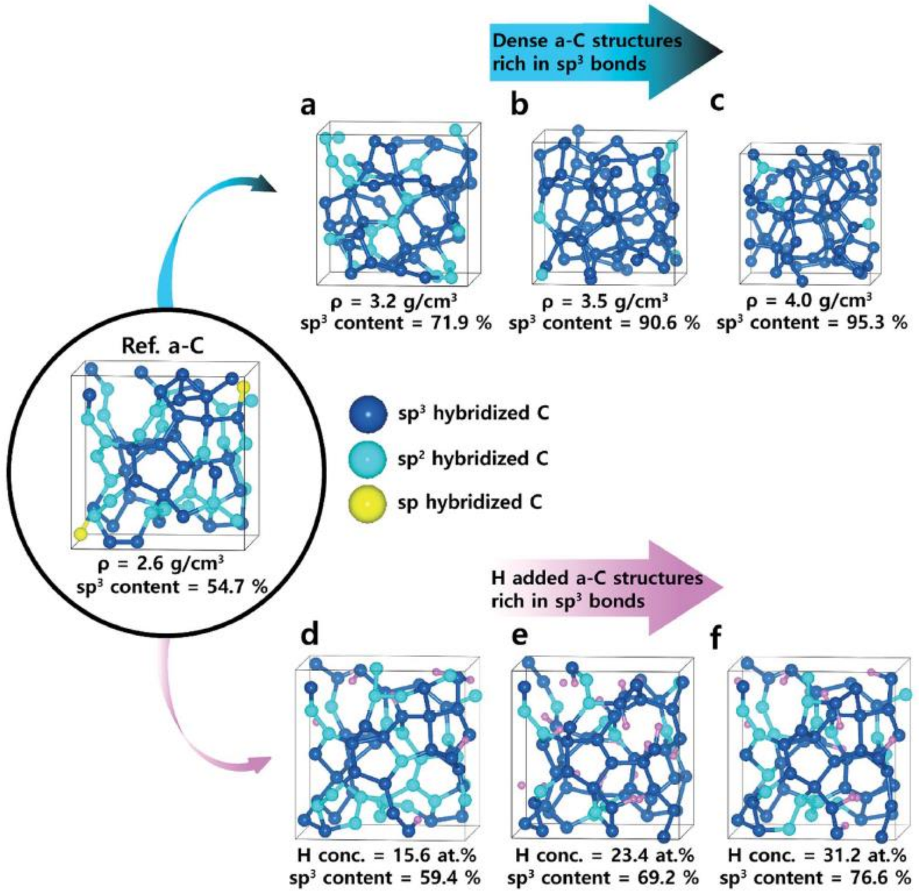
Source: LAM

a-Carbon Material Properties

Ternary Phase Diagram of a-C:H System



Bonding Structures in a-C, a-C:H Network



Increasing Density
High sp^3
High Bulk Modulus
High stress films

Increasing H-conc.
High sp^3
High Bulk Modulus
Lower stress films

Material property is a function of process temperature and chemistry

1. J. Robertson, Mat Sci and Eng. R 37, 129 -281 (2002)
2. J. Arlein et al. JOURNAL OF APPLIED PHYSICS, 104, 033508, 2008
3. H. Park et al. RSC Adv., 2020, 10, 6822

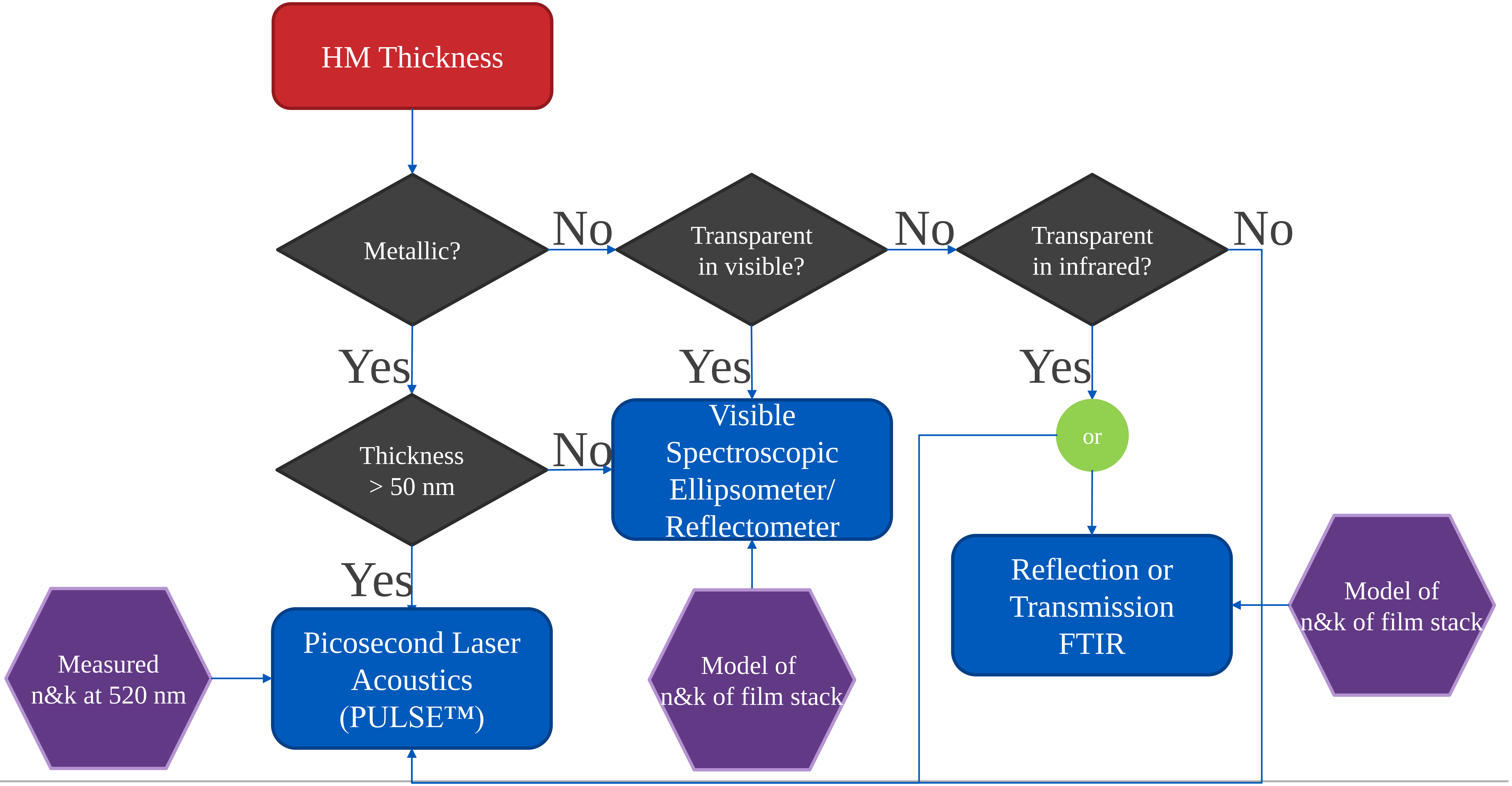
a-Carbon: Metrology Requirements

- Parameters of interest
  - Thickness
  - Optical constants
  - Density
  - sp^3/sp^2 hybridization
- Process Window ±0.7% on 2-3µm thick films

Shrinking process window → stringent metrology requirements

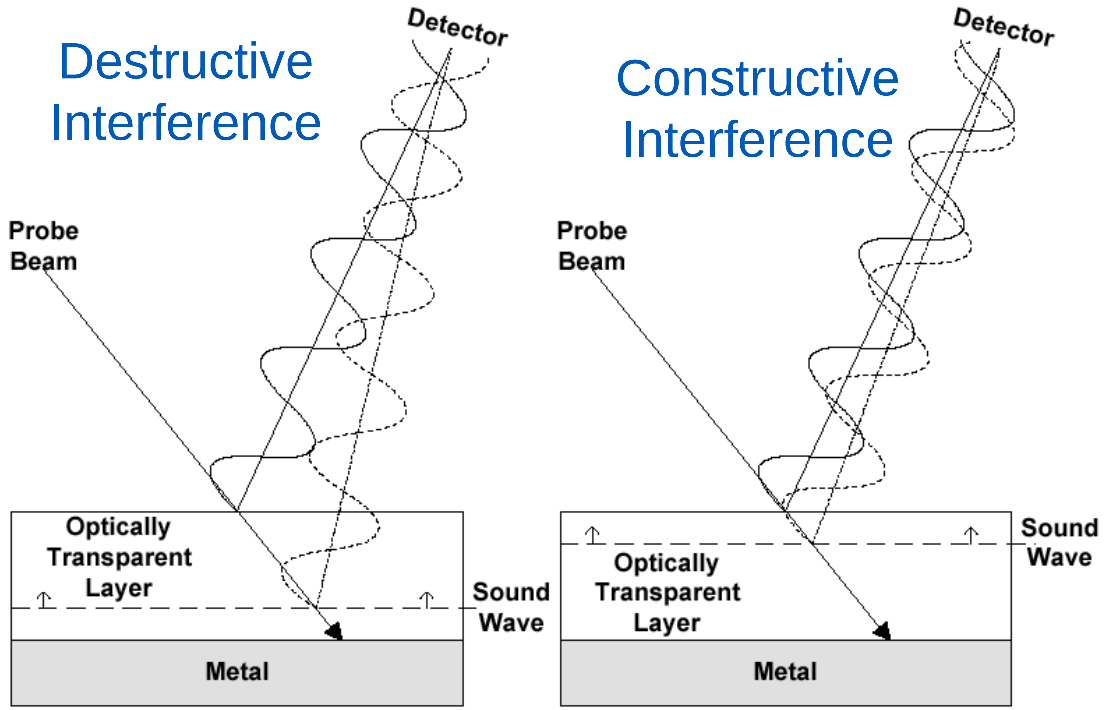
a-Carbon Materials Metrology

Non-destructive thickness metrology



a-C Films Measurement using PULSE™ Metrology

Schematic Representation



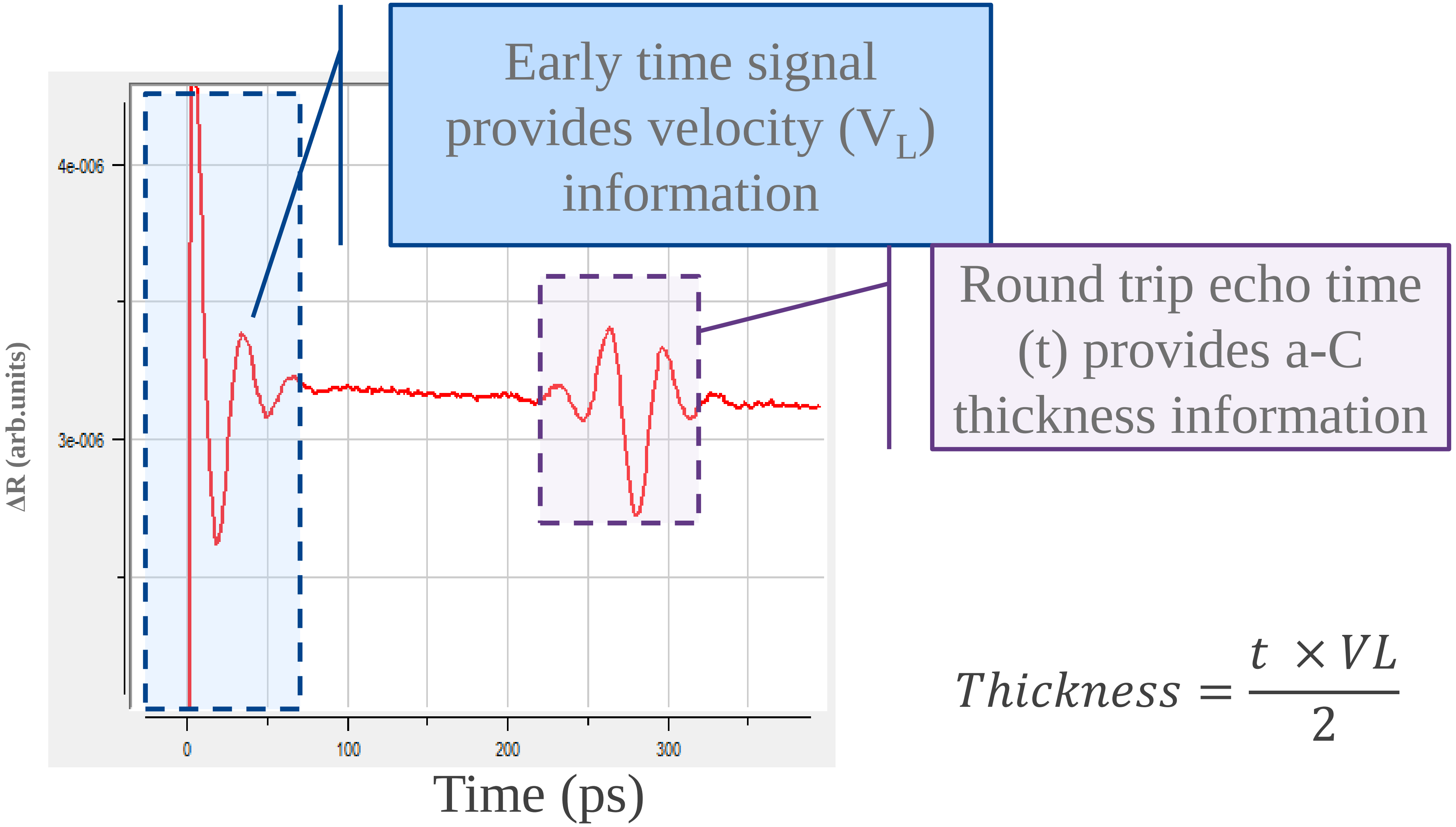
How it works

- Light from the pump beam excites a sound wave at the opaque substrate
- Light from the probe beam is reflected from the transparent film surface and from the travelling sound wave
- The reflected beams interfere at the detector, changing from destructive to constructive interference as the sound wave travels

$$V_L = \frac{\lambda}{2n\tau \cos\theta}$$

V_L longitudinal sound velocity
n index of refraction
λ wavelength of light
θ angle of incidence of light

Data Analysis of a-C Films using PULSE Metrology

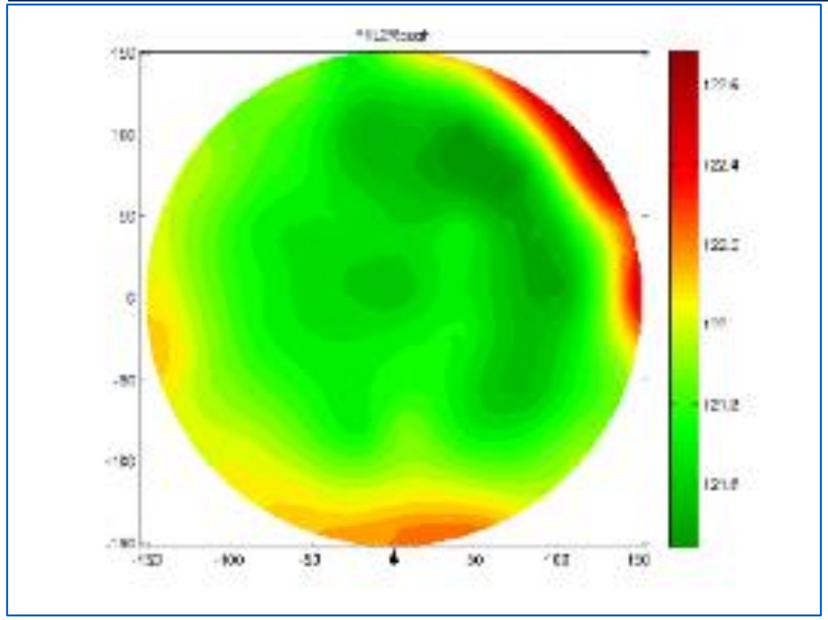


$$Thickness = \frac{t \times VL}{2}$$

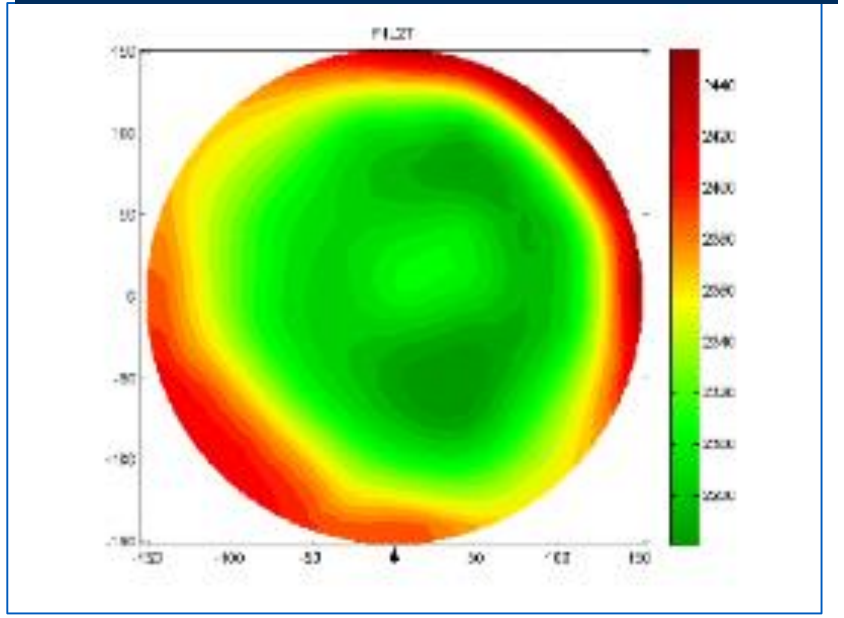
- First Principles Measurement
- Two parameters Thickness & Longitudinal Velocity measured
- Excellent signal to noise -> meets repeatability requirement

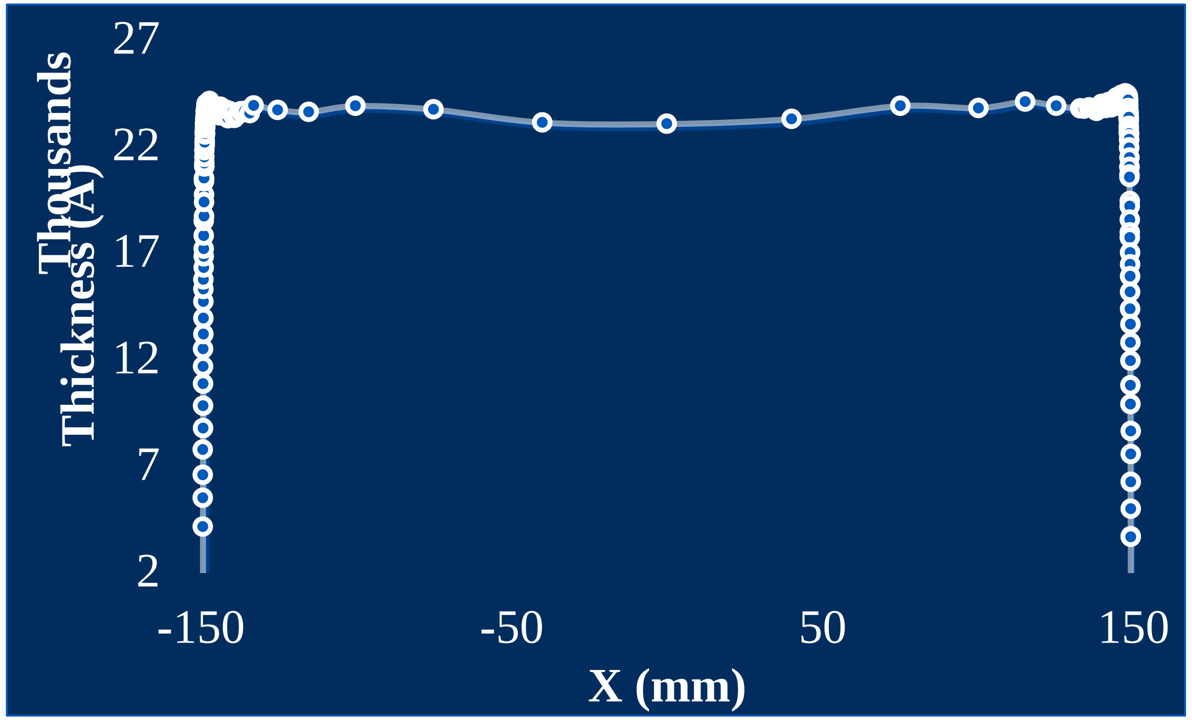
OEM Use Case: Process Development

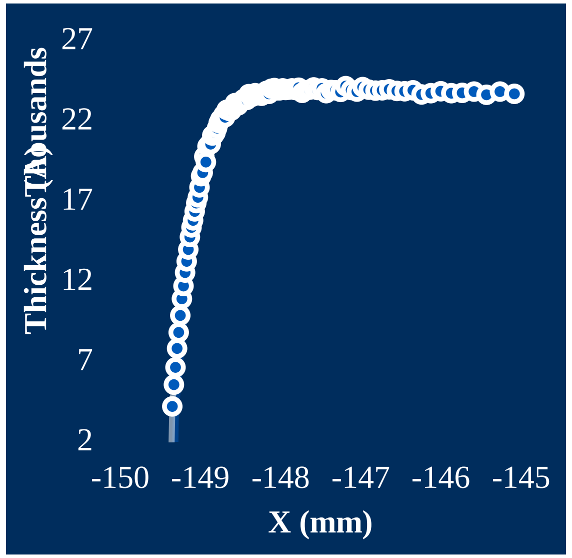
velocity

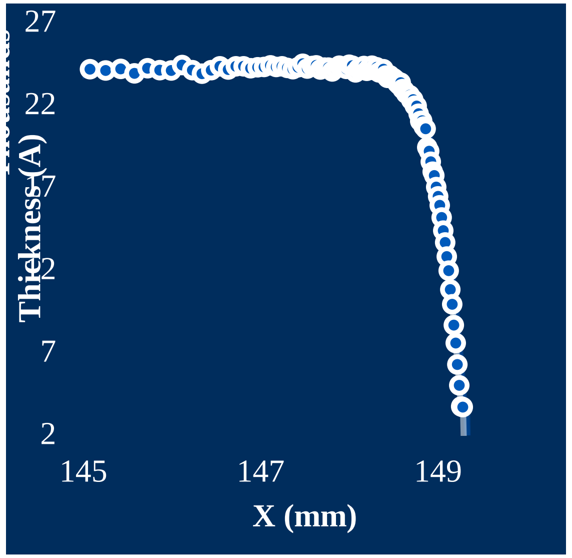


thickness



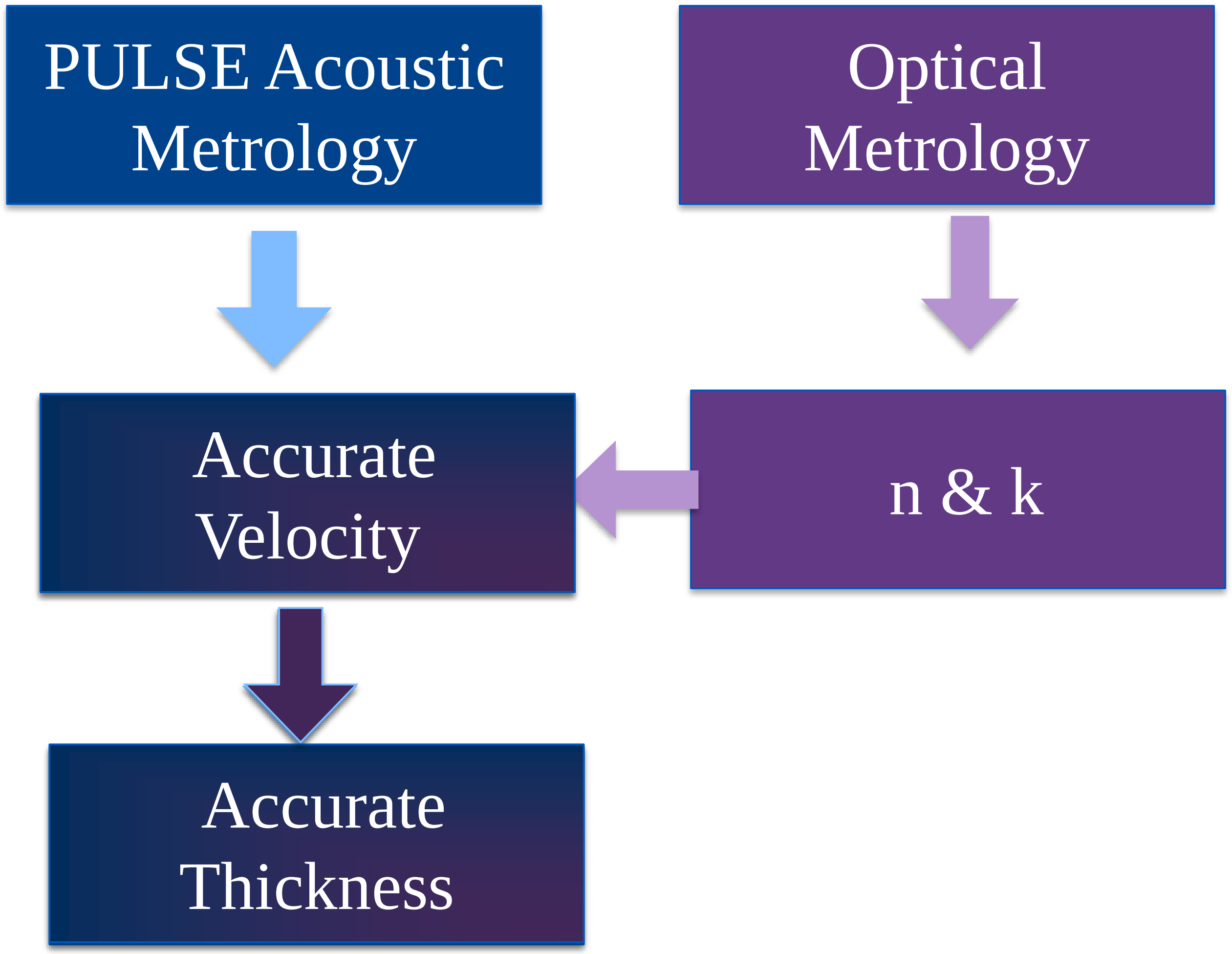


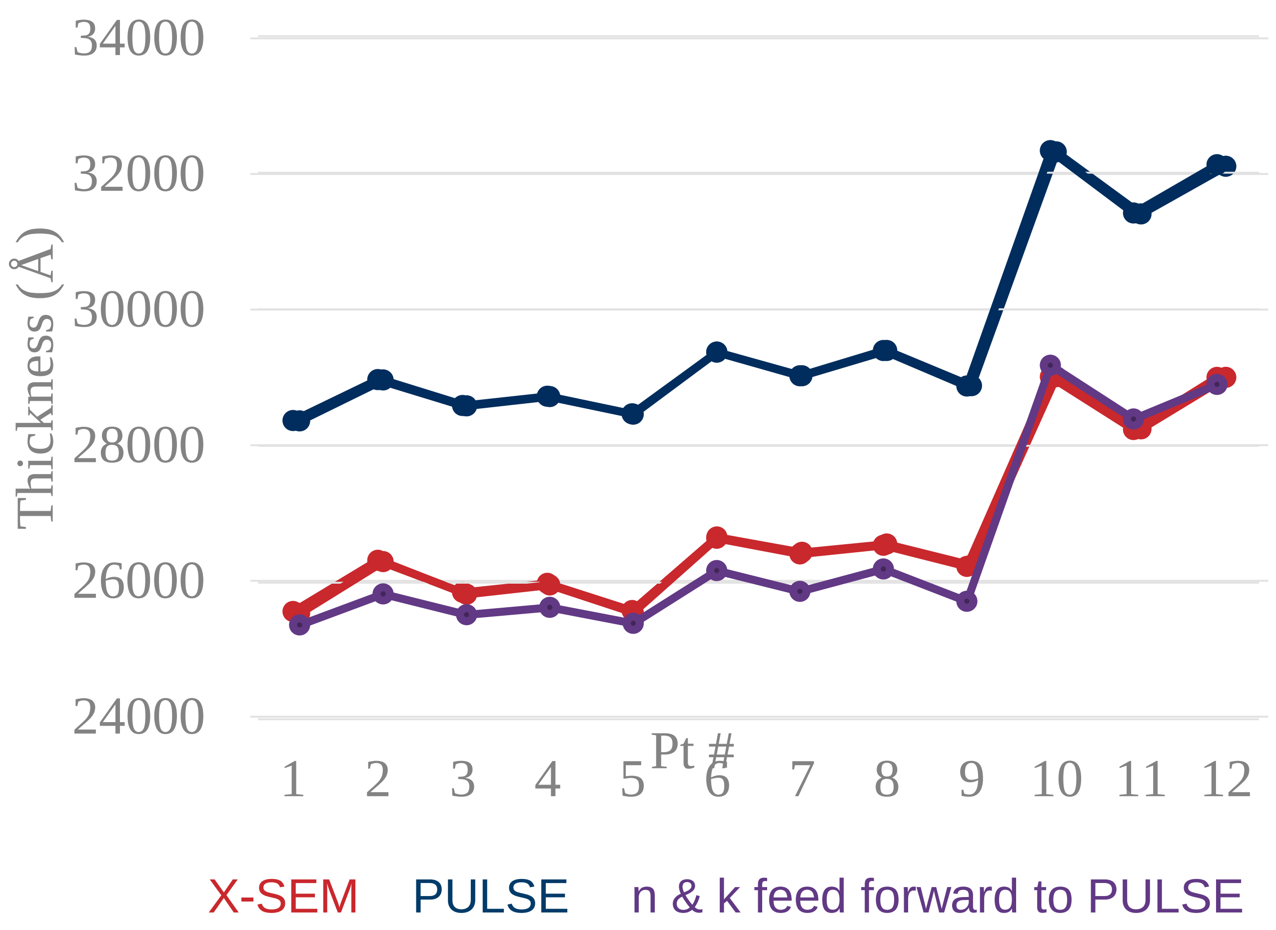




- Small spot ~Maps and high-resolution edge scans (0.5mm exclusion)
- Robust recipes to handle process changes

a-C: Correlation with X-SEM





With feed forward, thickness accuracy improved by 10X compared to X-SEM

Optical metrology: Atlas® III+

a-C: Sound Velocity, Young's Modulus & Etch Process

Etch profile evolution

- initial etch (<10s) – rapid
- bulk etch- slow and determines etch reaction rate

Etch profiles are controlled by tuning the **density** of the films

Bulk modulus α density

Absorption coefficient (k) used as *proxy* for density & bulk modulus

Non-destructive modulus measurement PULSE + Optical

$$V_L = \frac{\lambda}{2n\tau\cos\theta}$$

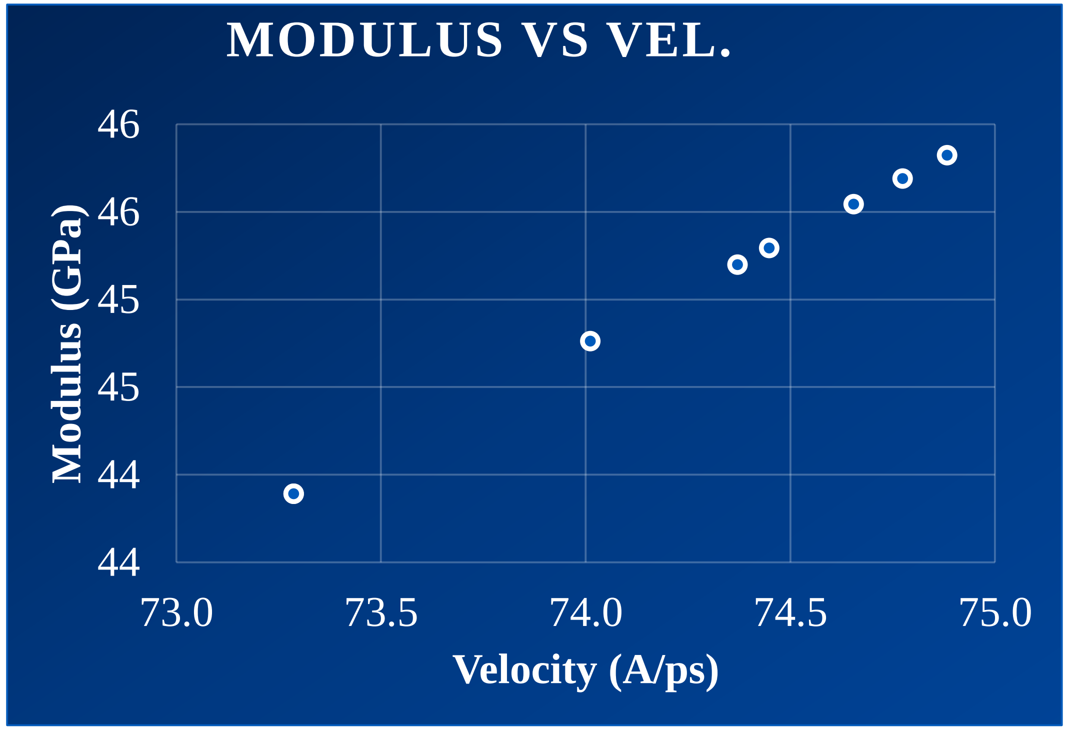
$$Y = \frac{(1-2\nu)(1+\nu)}{(1-\nu)}\rho V_L^2$$

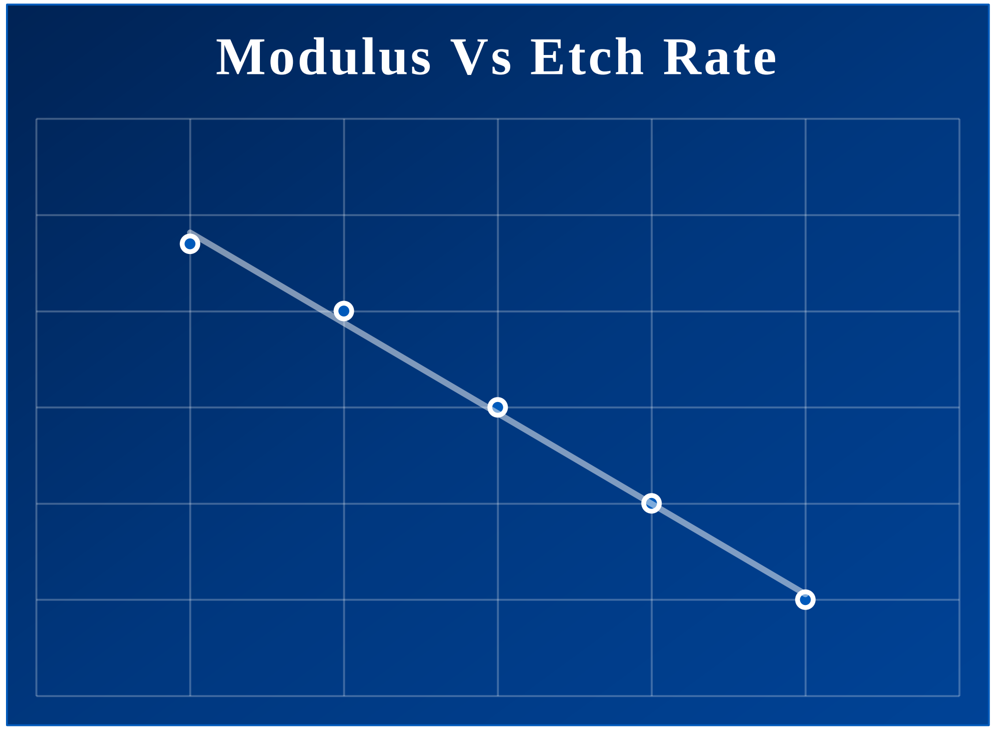
ρ is the film density (input)
ν is the Poisson's ratio (input)

Sound velocity provides a direct measurement of modulus and used in etch process monitoring & control

J. Robertson, Diamond Relat. Mater. 2,984-989, 1993
A. M. Ito et al. J. Phys. Conf. Ser., 518, 012011, 2014

Young’s Modulus & Etch Process



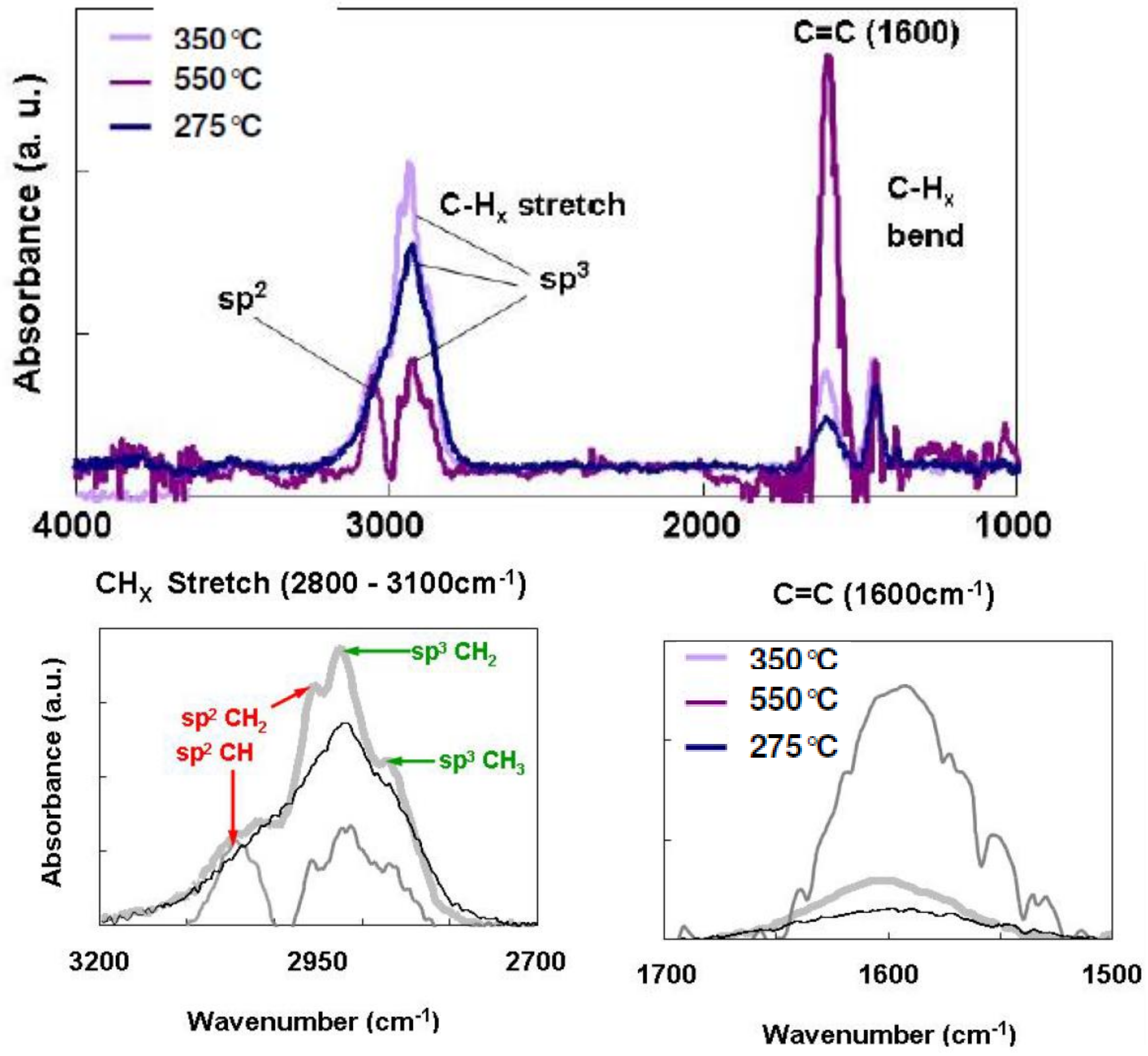


Direct correlation between modulus and velocity

Inverse correlation between modulus and etch rate

a-C: Characterizing with FTIR

a-C films: Summary of properties



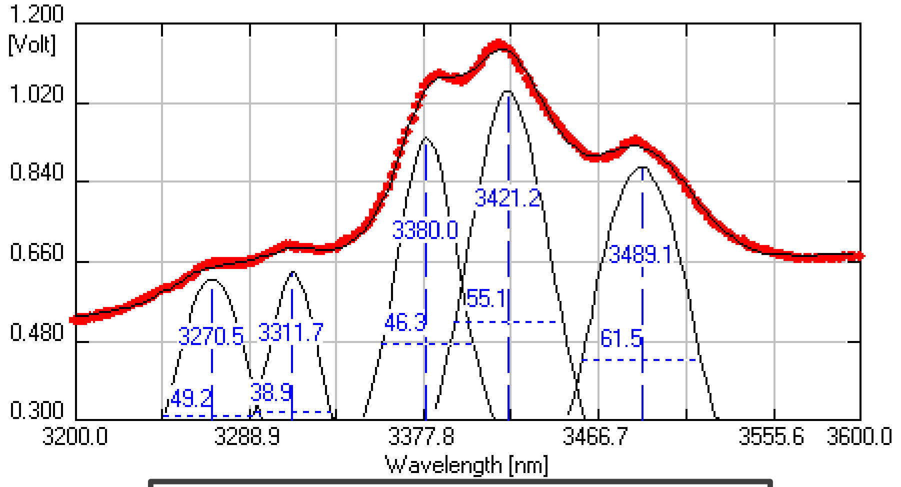
Dep. Temp. (°C)	% C by atom	% H by atom	n @ 633nm	k @ 633nm	Density (g/cm^3)	Hardness (GPa)
350°C	56	42	1.81	0.05	1.23	2.7
550°C	70	27	2.00	0.38	1.44	1.8
275°C	60	40	1.99	<0.10	1.48	9.5

Sample at 550°C is significantly more sp^2 (graphitic) compared to other two samples

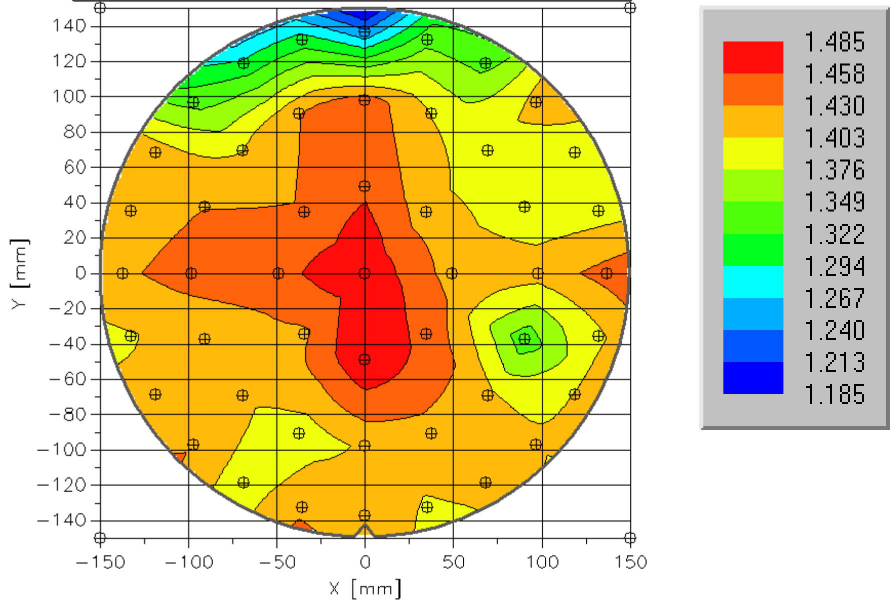
CH$_x$ stretching vibrations of the Type 2 network have more sp^2 CH$_2$ (2950 cm^{-1}) and sp^2 CH (3050 cm^{-1}) bonds compared to sp^3 bonds

A. Antonelli et al. ECS Transactions, 35 (4) 701-716 (2011)

a-C: FTIR Measurements from a 5000Å film



Peak deconvolution –wafer center



Assignment	Predicted wavenumber (1/cm)	Measured wavenumber (1/cm)
sp2 CH2 (olefinic)	3020	3020.02
sp3 CH3 (asymmetrical)	2960-2970	2959.31
sp3 CH2 (asymmetrical)	2920-2925	2923.55
sp3 CH3 (symmetrical)	2865-2875	2866.27

Characterization of the bonding structure of the materials using transmission FTIR
sp3/sp2 ratio information obtained helpful during process development

Summary

- A-Carbon films are critical in the 3D NAND process.
- Thickness and elastic modulus are important to define channel hole and to tune etch profile, respectively
- Multiple metrology tools are used to comprehensively characterize this complex system
  - PULSE Acoustic metrology provides thickness and velocity.
  - Velocity is directly correlated to elastic modulus
  - In combination with optical metrology, it enables tuning of etch process for high aspect ratio structures
  - FTIR has found adoption as complementary technique to provide information on the bonding structure of the films

Acknowledgment

- A. Antonelli for valuable discussions & insights into the a-C hard mask deposition and metrology development
- R. Mair, J. Dai and the Applications Team at Onto Innovation