Diamond-Like Carbon for potential use as protective and high emissivity coating for future mirror suspensions

Ross Birney[1], Stuart Reid[1], Alan Cumming[2], Giles Hammond[2], Jim Hough[2], Iain Martin[2], Sheila Rowan[2].
1 – SUPA, University of the West of Scotland
2 – SUPA, University of Glasgow

LVC 2014 at Stanford University
Tuesday, August 26th, 2014

DCC G1400975

Thin Film Centre at UWS

- Research facility created in 1999 in the University of the West of Scotland (Paisley).
  - Located approx. 10 km from The University of Glasgow.
- Aim of developing thin film deposition technology (particularly for industry).
- Commercial-scale deposition and characterisation equipment.

- Joined GEO and the LSC in September 2012 (group led by Reid).

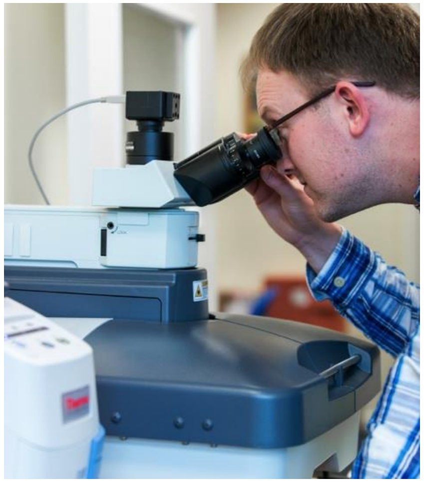
Facilities

Deposition techniques

- Microwave-activated reactive sputtering
- RF and DC sputtering
- PECVD
- Plasma-assisted e-beam (evaporation)
- *Recently purchased two ion sources for developing IBD*
- *Developing/characterising MBE with an industrial partner*
- *Currently developing optical coatings*

Characterisation techniques include:

- SEM with EDX
- Raman Spectroscopy, FTIR
- Kelvin probe
- Surface energy (Contact angle)
- XRD
- Nanoindentor/microindentor & AFM
- Hardness/scratch/adhesion

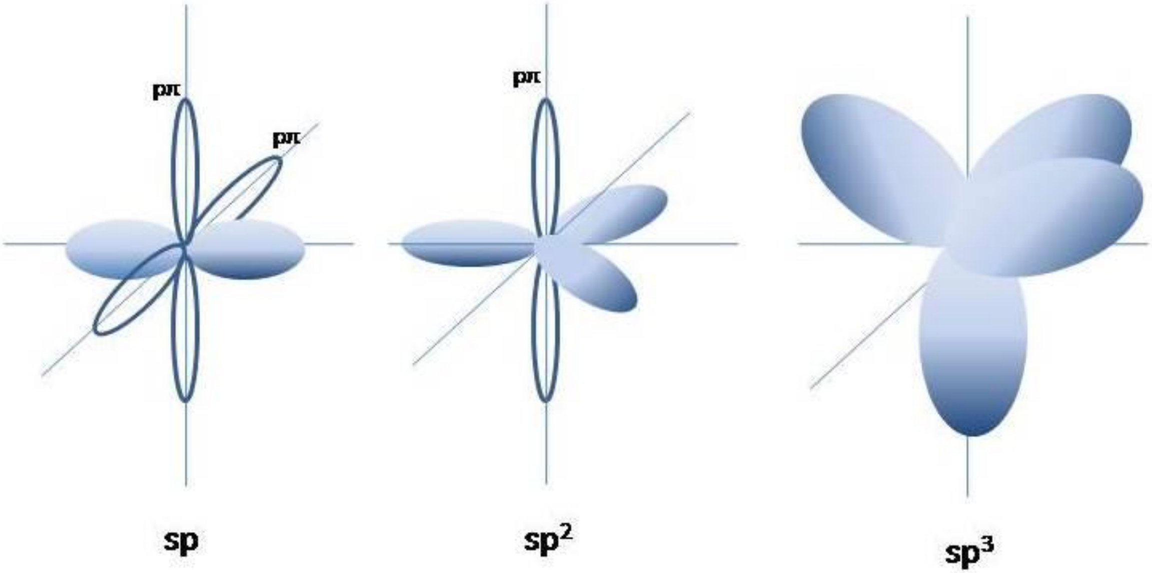


DLC: Diamond-like Carbon applications in GW detectors

- The relatively **high emissivity** of DLC may be beneficial for cryogenic applications:
  - KAGRA are to coat baffle tubes with DLC for this purpose.
  - Compatible with UHV bakeout
  - Currently working on experimental coatings for VIRGO baffle tubes (SS304) – multilayer modified DLCs at 2, 10 and 20μm total thickness
- The properties of DLC are attractive for use as a **protective** coating:
  - Can fabricate pinhole-free, relatively thick DLC using the hollow cathode CVD technique
  - Evaluation of using DLC for protecting low mechanical loss suspension components for future GW detectors
    e.g. coating cantilever springs (silica, silicon, sapphire) for reducing vertical thermal noise – see later.

DLC – Diamond-Like Carbon

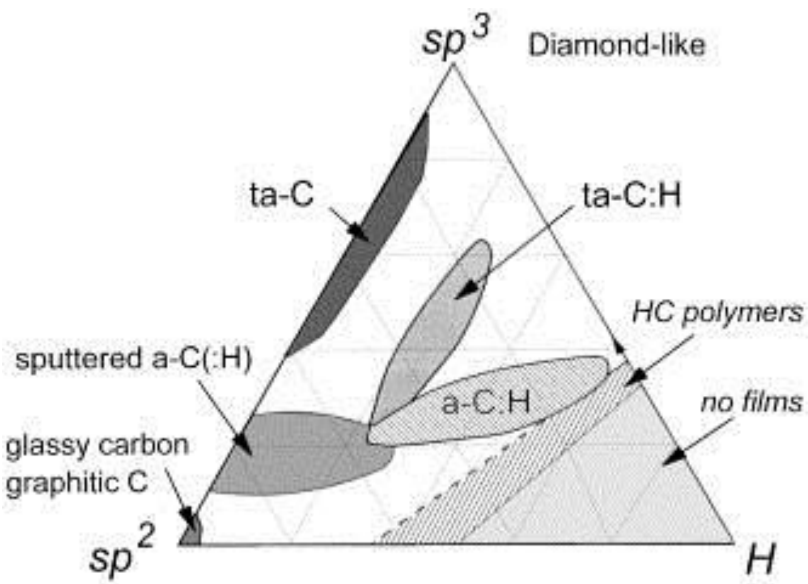
- Metastable form of amorphous carbon
- Consists of network of tetrahedrally and/or trigonally bonded carbon atoms as well as hydrogen (in some cases)
- Bonding varies from 100% sp2 (graphitic) to ~90% sp3 (similar to diamond)



Three hybridisations of carbon

DLC (continued)

- Term DLC can refer to several classes of material:
  - ta-C – tetrahedral amorphous carbon has up to 90% sp3 fraction
  - ta-C:H – tetrahedral hydrogenated amorphous carbon
  - a-C – amorphous carbon with <90% sp3 fraction
  - a-C:H – hydrogenated amorphous carbon (carbon-hydrogen alloys)

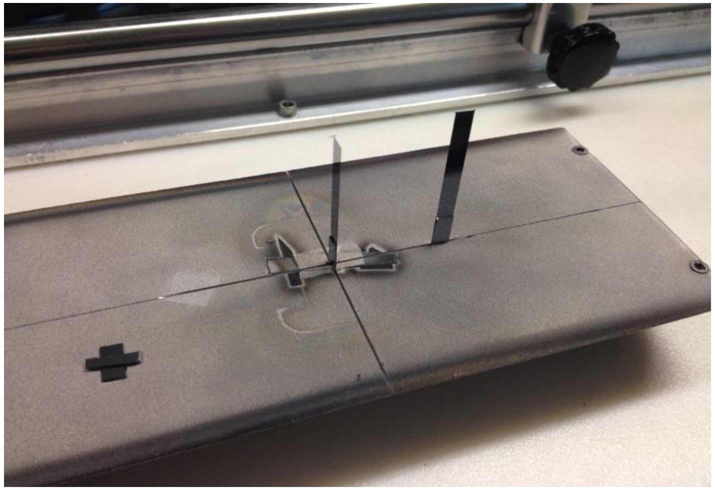


A ternary phase diagram relating the compositions of the various amorphous carbons and amorphous carbon-hydrogen alloys [1]

[1] J. Robertson, Jpn. J Appl. Phys. 50 (2011) 01AF01

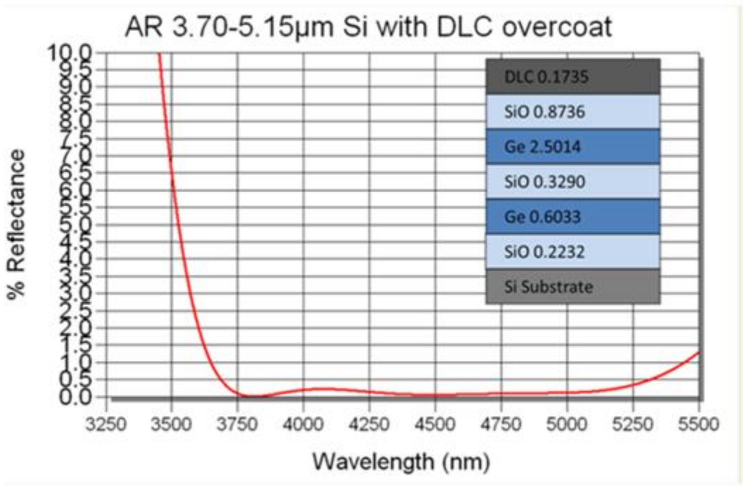
Properties of DLCs

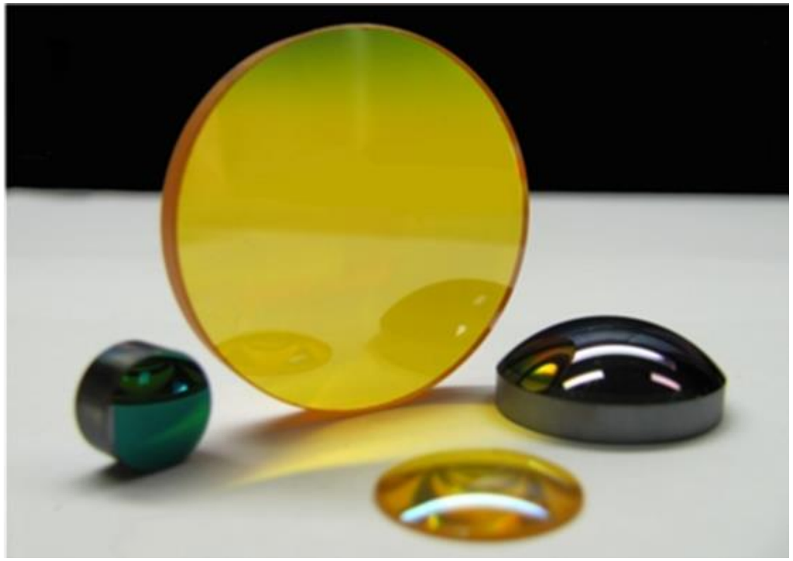
- Hard – typically ~12GPa (a-C:H type), E_R~100-120GPa
- Excellent protective properties :
  - Anti-corrosive
  - Smooth, conformal coating (non-directional deposition process)
  - Despite high intrinsic stress, can deposit multilayers up to ~70µm total thickness
  - Low-friction – useful in e.g. engine components
  -High emissivity
  -Largely transparent in infrared – useful in IR optical coatings



Synthesis and applications

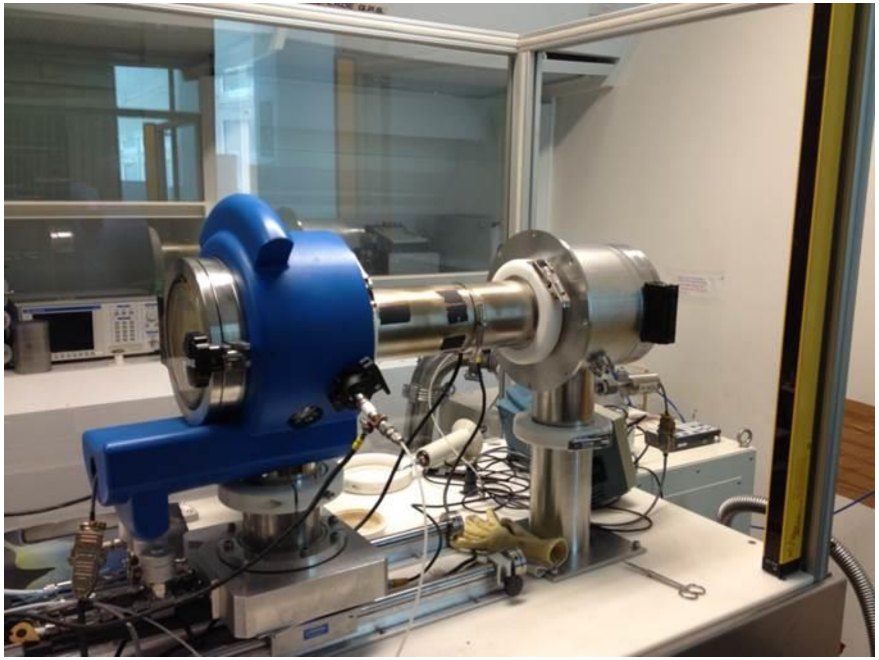
- Deposition by a wide range of methods including PECVD, HC-PECVD, RF sputtering, evaporation, MSIBD, pulsed laser deposition
- Applications include infrared optics, gas barrier coatings, protective coatings for corrosive / abrasive environments, accelerator coatings
- Not currently being considered for use in GW detector mirror coatings





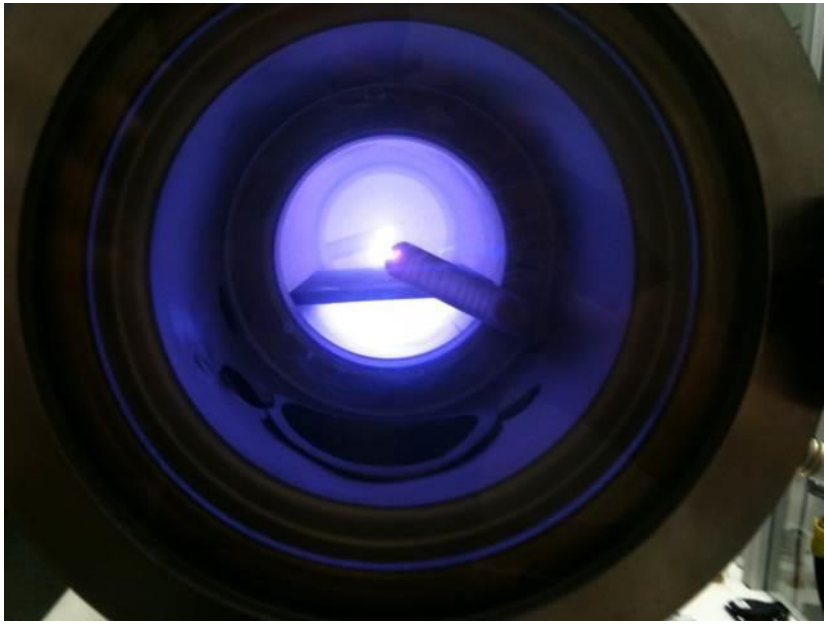
UWS DLC Process

- Hollow cathode PECVD
- Pulsed-DC waveform applied to enable dissipation of charge during off cycle (DLC is insulative, and charging of growing film will eventually lead to arcing and pinholing of coating)
- Multilayer or single-layer process utilising hydrocarbon and other precursors
- Can deposit hydrogenated DLC, modified
  DLC, a-Si:H,
  a-Si:C, a-Ge:C…

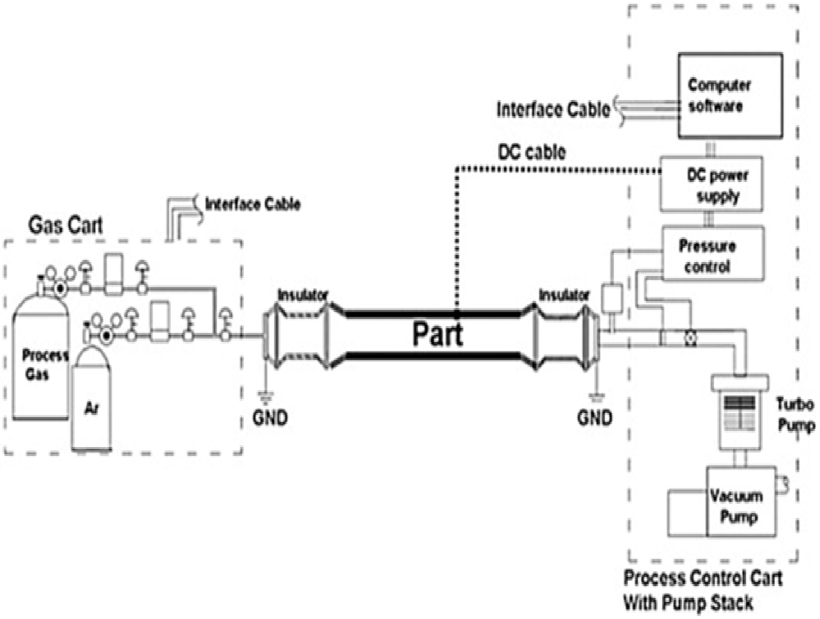


Coating Deposition – HC-PECVD

- System can accommodate various lengths / diameters of pipe
- Modification of system allows coating different substrate geometries: flat, irregularly shaped, exterior pipe surfaces, fibres (in theory)



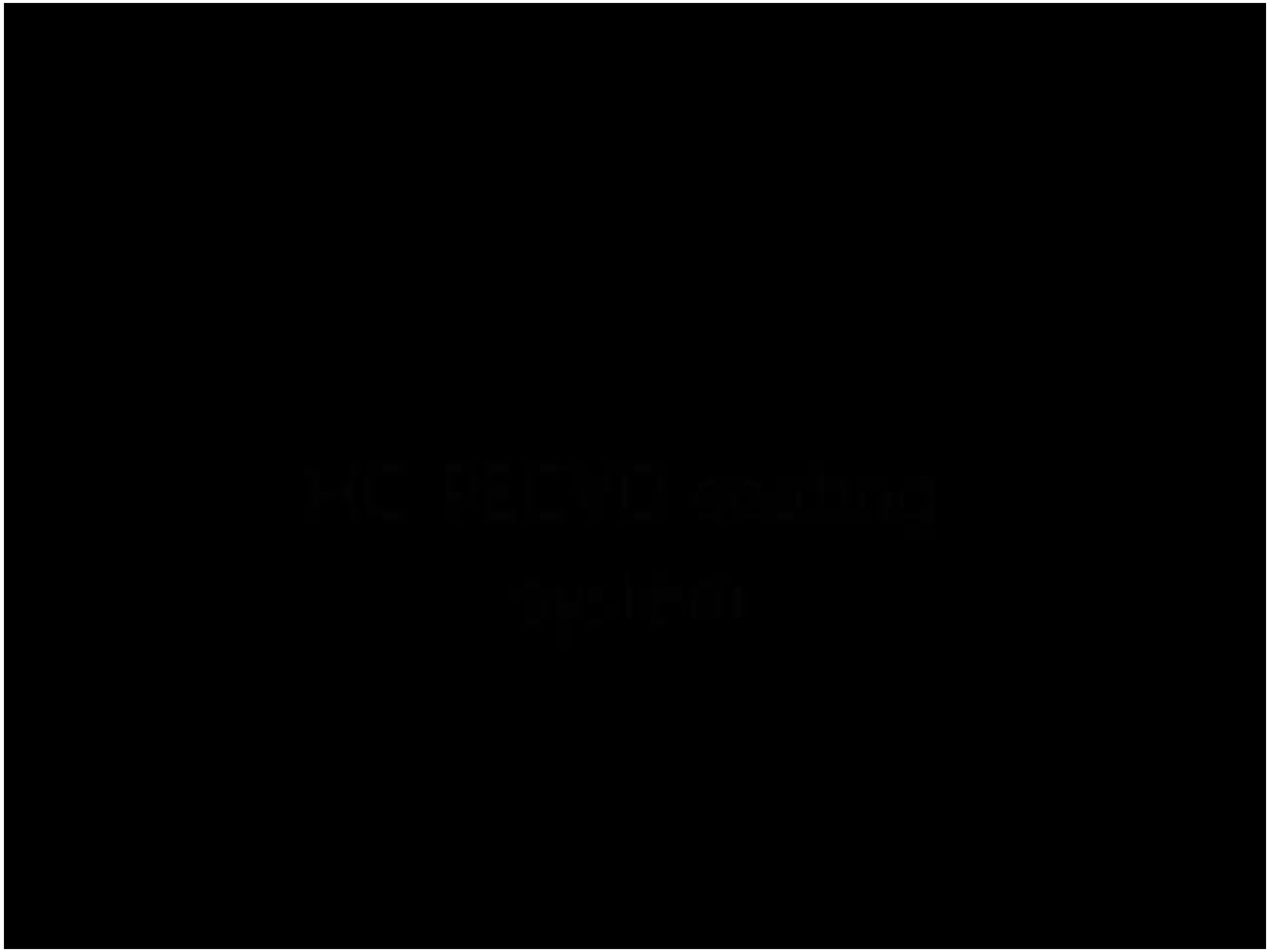
HC-PECVD system, 4x12" pipe chamber with Al stage (Thin Film Centre, UWS)



Schematic of hollow cathode pulsed-DC PECVD system [2]

[2] D.Lusk, M.Gore, W. Boardman, T.Casserly, K.Boinapally, M.Oppus, D.Upadhyaya, A. Tudhope, M. Gupta, Y.Cao, S.Lapp, Diamond Rel. Mater. 17 (2008) 1613

Sub-One Technology HC-PECVD System



DLC: thermal noise (on sapphire cantilever spring)

- Mechanical loss of DLC on silicon at room temperature ~ 3×10^{-4}.

FEA model of a single KAGRA fibre, of IMPEX style, with a prototype sapphire blade spring.
NO COATING YET!

See talk by A. Cumming (ET Meeting, Hannover, Oct 2013)

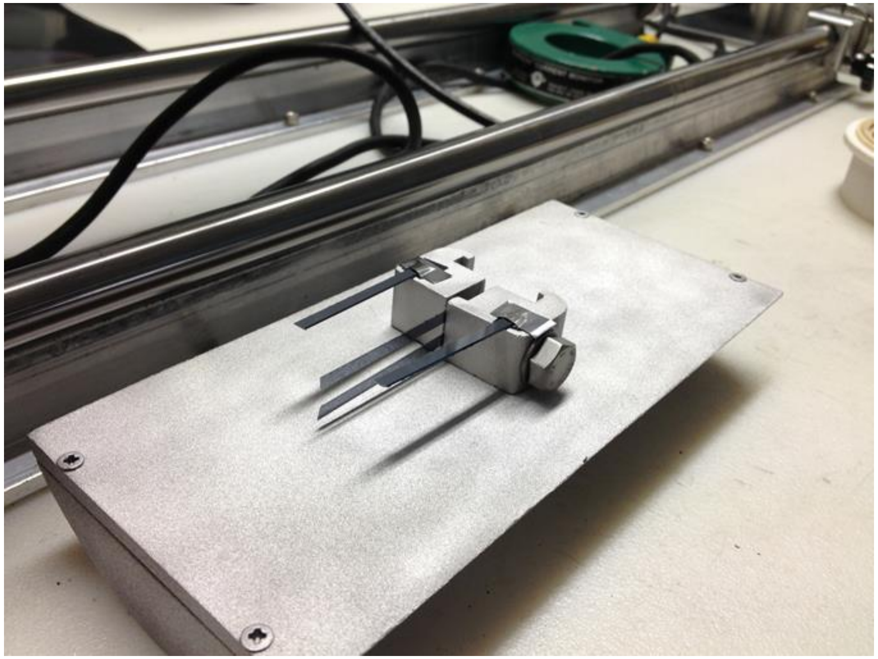
- Sapphire suspension – without DLC coating applied:

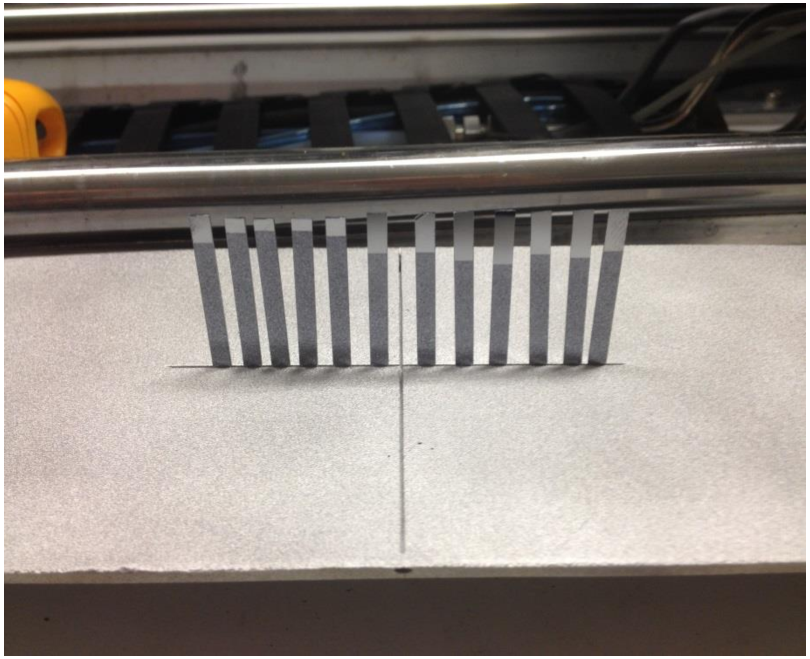
Component	Energy ratio %	Loss of component	Loss contribution to total
Fibre main section	97.38	4.44E-07	4.32E-07
Fibre ends	1.38	8.00E-08	1.44E-09
Blade	1.24	5.2E-10 at 10Hz	6.45E-12 at 10Hz
Blade clamps	0.0036	1.00E-04	3.65E-09
Connection - Bond	0.0013	Yet to be measured	
		Total loss	4.36E-07
		Dissipation dilution	13.5 (6.75)
		Pendulum mode loss	3.3E-08 (6.6E-8)

- Energy ratio for 1 μm DLC on 1 mm thick Al_2O_3 cantilever spring is ~ 4×10^{-3}, contributing to a loss of 1×10^{-6}.
- Contribution to loss of bounce mode of suspension is 1.24% and therefore ~1×10^{-8} (approx. 2% vertical suspension TN).
- Can be reduced by reducing DLC thickness (and lower T?).

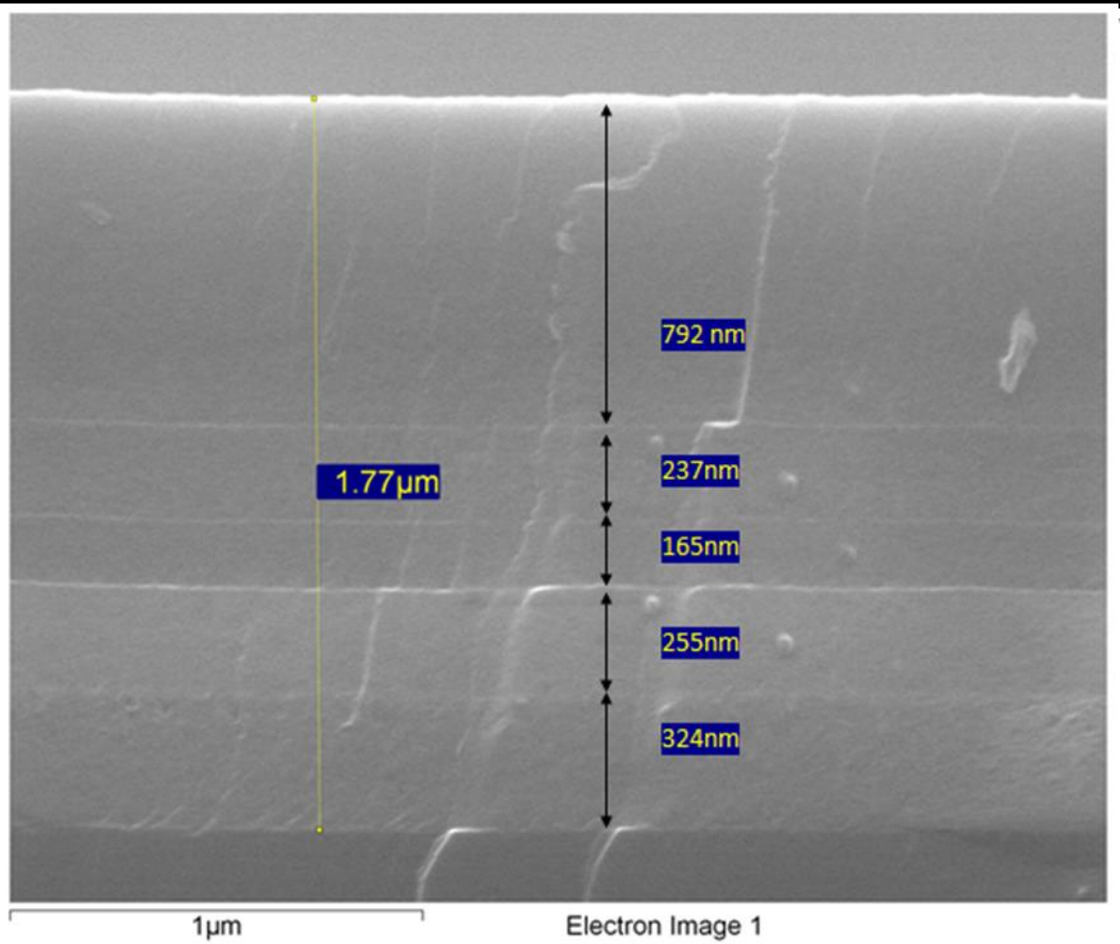
Strength testing of Multilayer DLCs for silicon suspensions

- 5-layer modified DLC coatings tested at 3.5μm total thickness
- Initial results encouraging, showing improvement of breaking stress in some cases
- Greater sample population needed!



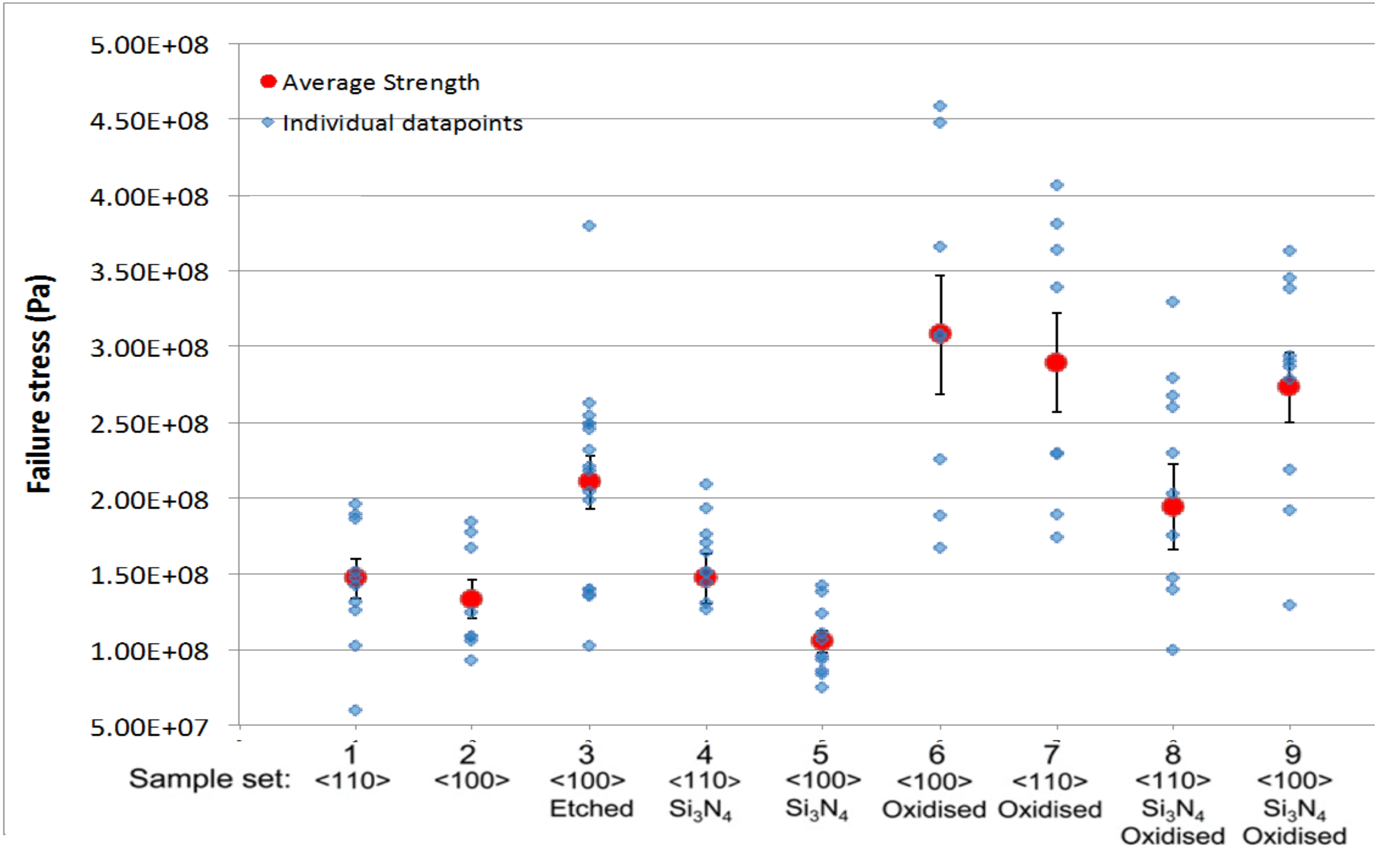


5-layer modified DLC on Si substrate



- *SEM cross-section of 5-layer modified DLC deposited on silicon by HCPECVD at 400W power.*

Cumming *et al.*, Class. Quantum Grav. 31 (2014)



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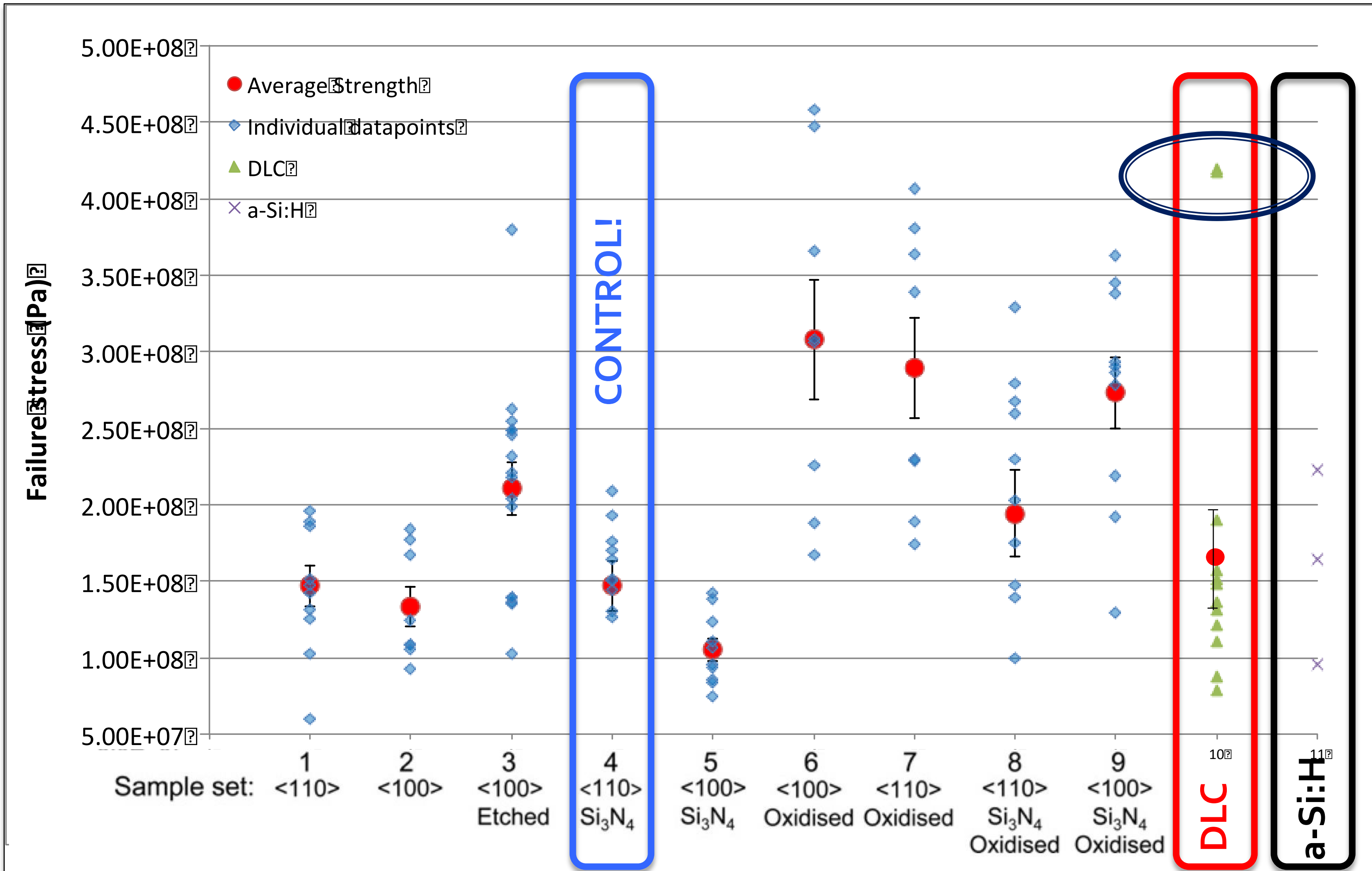


Coating strength testing (currently underway)

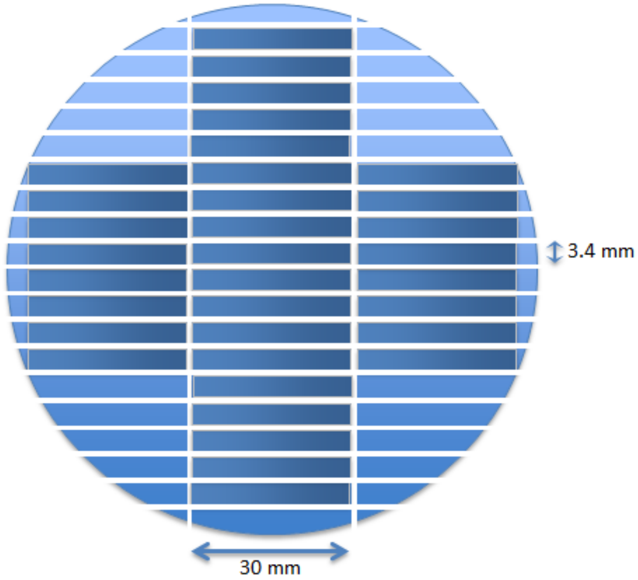
- Silicon diced, unpolished edges:

-12 silicon strips
-12 silicon strips, no polishing + extended Ar etch
-12 silicon strips, no polishing + single layer DLC
-12 silicon strips, no polishing + extended Ar etch + single layer DLC *
-12 silicon strips, no polishing + multilayer DLC
-12 silicon strips, no polishing + extended Ar etch + multilayer DLC *
-12 silicon strips, no polishing + magnetron silica coating
-12 silicon strips, no polishing + extended Ar etch + magnetron silica coating *

- Silicon diced, polished edges:

-12 silicon strips, edge polished
-12 silicon strips, edge polished + extended Ar etch
-12 silicon strips, edge polished + single layer DLC
-12 silicon strips, edge polished + extended Ar etch + single layer DLC *
-12 silicon strips, edge polished + multilayer DLC
-12 silicon strips, edge polished + extended Ar etch + multilayer DLC *
-12 silicon strips, edge polished + magnetron silica coating
-12 silicon strips, edge polished + extended Ar etch + magnetron silica coating

Silica/silicon 4" wafer
(5 wafers of each)



- Multilayer DLC coatings are ~3.5µm thick, single-layer coatings are 1µm thick
- To be repeated for silica and sapphire substrates too

Conclusions

- DLC on test silicon suspension shows no significant loss in strength compared to the control / untreated Si (evidence that DLC coatings may increase strength) – further work with a much greater number of samples is underway
- DLC will contribute negligible thermal noise associated with cantilever springs
- Future work includes:
  - Measurement of mechanical strength and mechanical loss at low T of DLC coated components.
  - Investigate DLC coatings on silica and sapphire – substrates available
  - Studies on the effect of clamping/jointing DLC coated cantilever springs
  - Investigate DLC coatings on silicon and sapphire suspension fibres (here the mechanical loss and relative thickness of the DLC films are critical in the suspension thermal noise – more challenging).
  - Some studies are underway on coating silicon suspensions with a thin layer of a-Si:H to evaluate the effect on strength (e.g. from filling in microcracks from manufacturing process) and on thermal noise

Acknowledgements

Thanks to Dr Liz Porteous at UWS for SEM imaging and Gerry O'Hare for (much) substrate preparation.

Thank you for your attention!