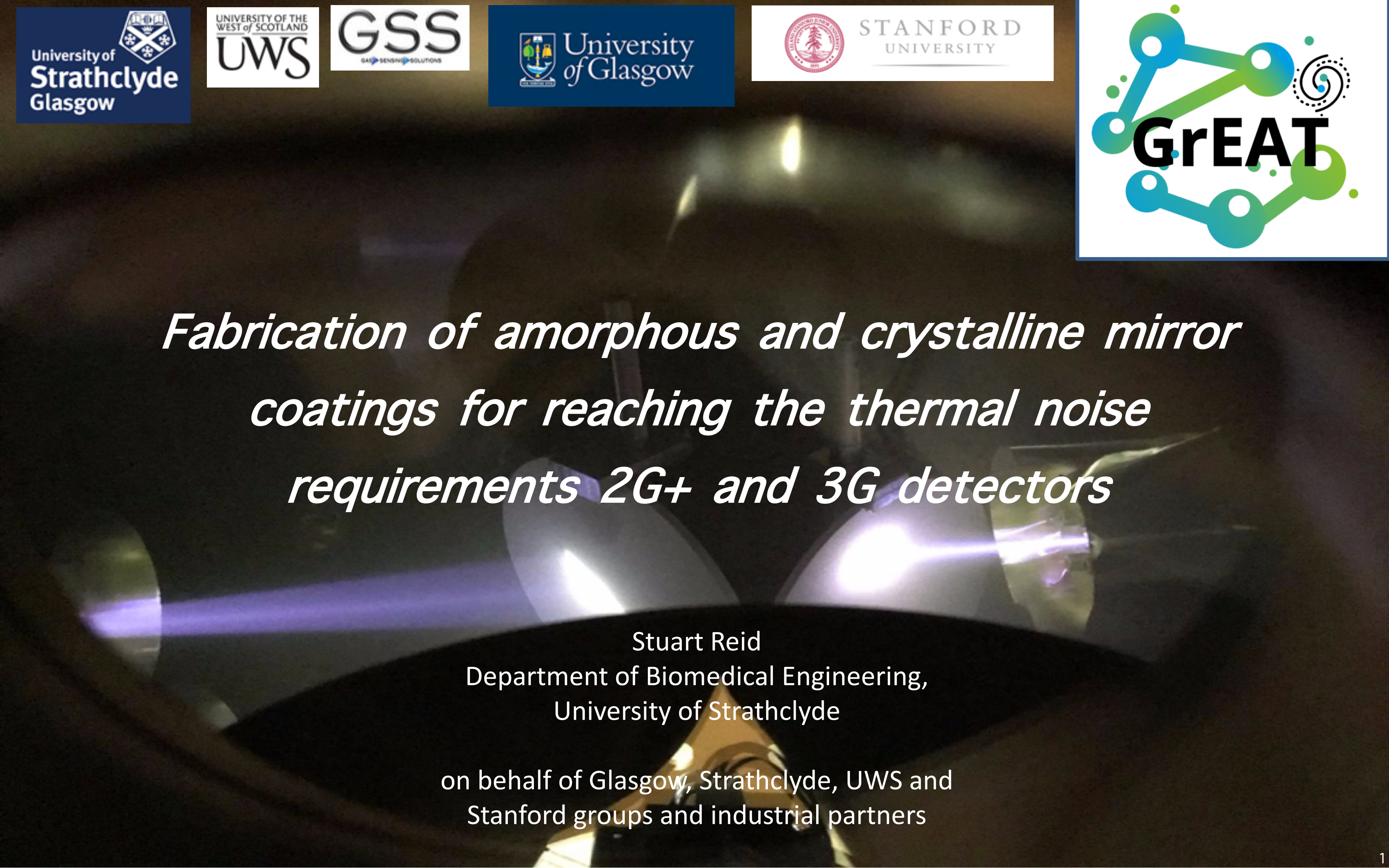


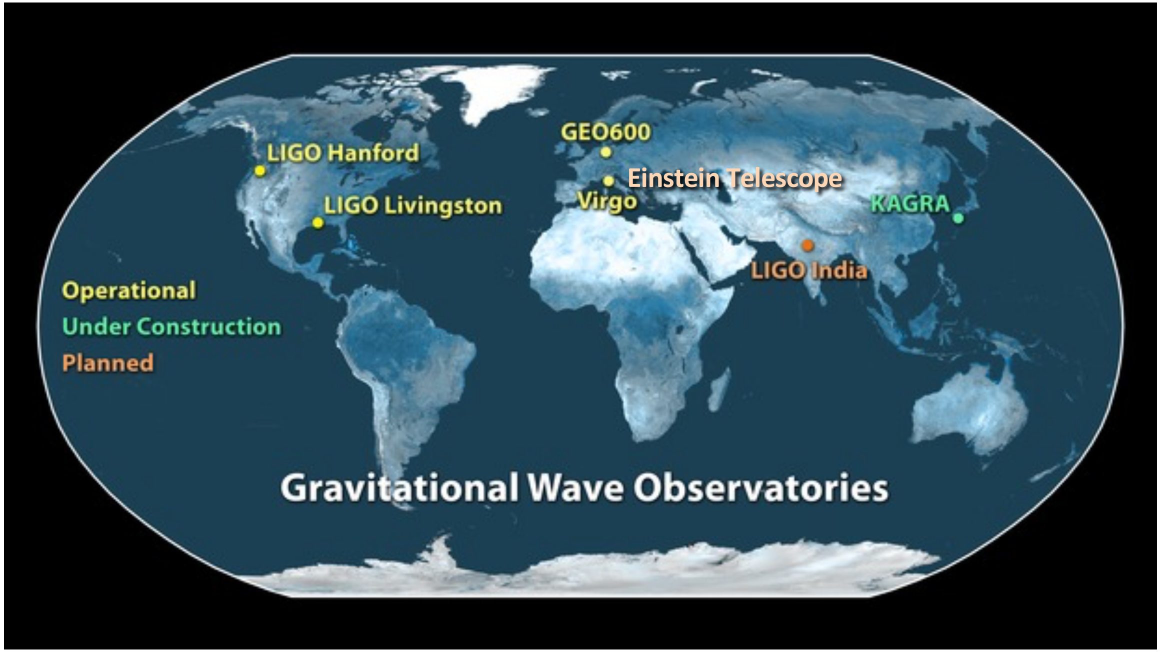
Fabrication of amorphous and crystalline mirror coatings for reaching the thermal noise requirements 2G+ and 3G detectors

Stuart Reid
Department of Biomedical Engineering,
University of Strathclyde

on behalf of Glasgow, Strathclyde, UWS and
Stanford groups and industrial partners

Long-term collaborations in GW networks

Towards the future GW network



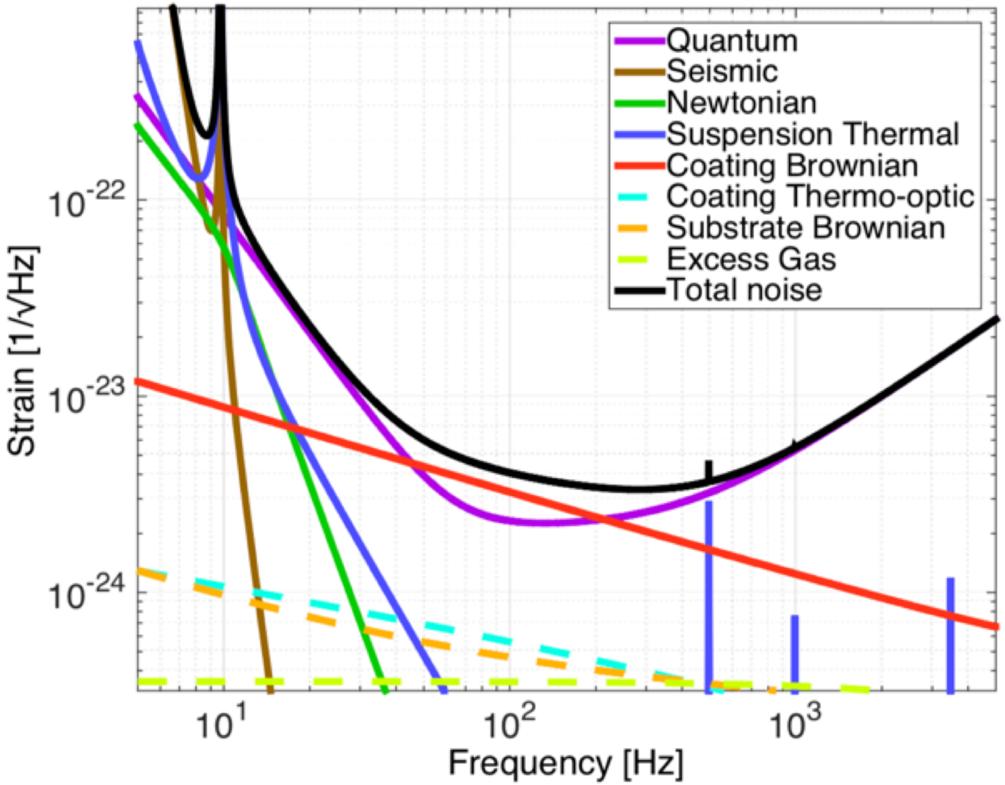
LSC LIGO Scientific Collaboration

KAGRA

ET EINSTEIN TELESCOPE

Cosmic Explorer

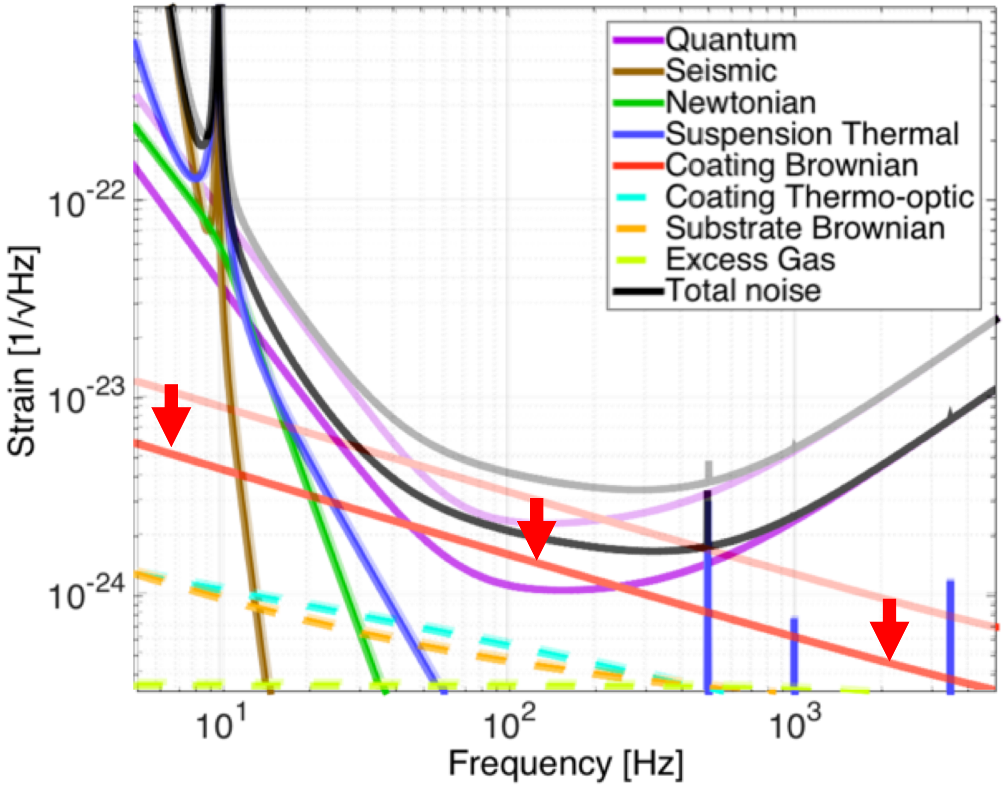
Focus largely on A+



LIGO India will be constructed as an A+ instrument

Factor 4 reduction in coating loss (factor 2 in strain noise) required by 2020!

Focus largely on A+



LIGO India will be constructed as an A+ instrument

Factor 4 reduction in coating loss (factor 2 in strain noise) required by 2020!

A+ (funding announced Feb 2019)

NEWS · 15 FEBRUARY 2019

Gravitational-wave observatory LIGO set to double its detecting power

A planned US$35-million upgrade could enable LIGO to spot one black-hole merger per hour by the mid-2020s.

Davide Castelvecchi

RELATED ARTICLES

Gravitational-wave astronomers detect hints of largest black-hole merger yet

Japan's pioneering detector set to join hunt for gravitational waves

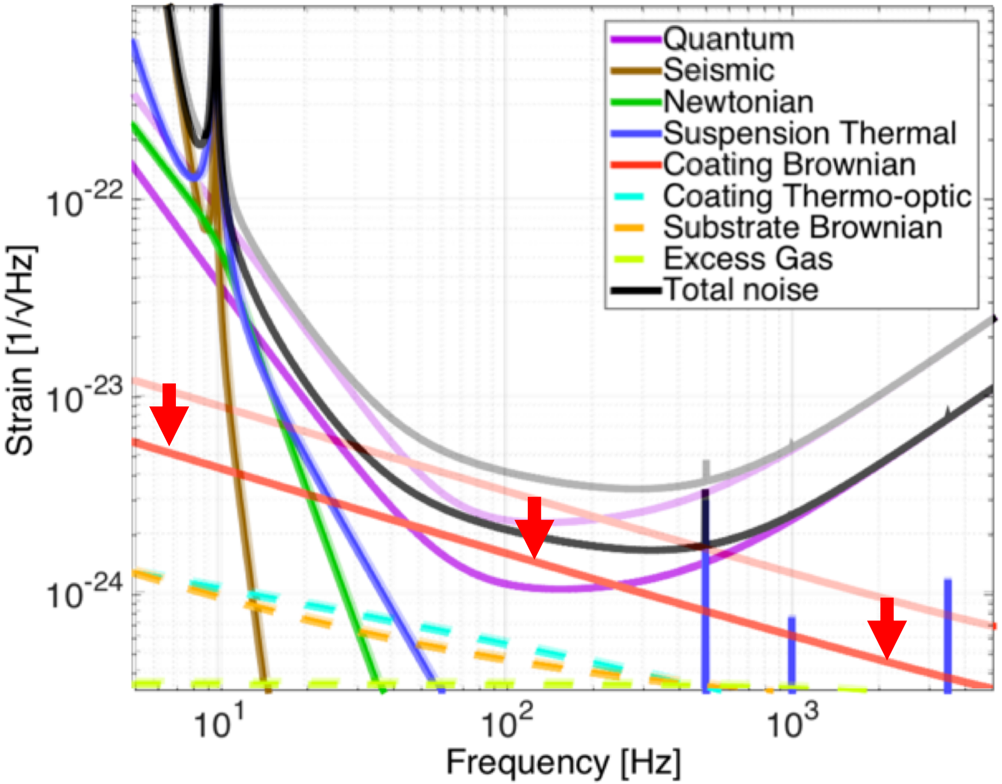
Tricks to mute quantum noise aid hunt

Science & Environment

LIGO gravitational waves: Black hole detectors to get upgrade

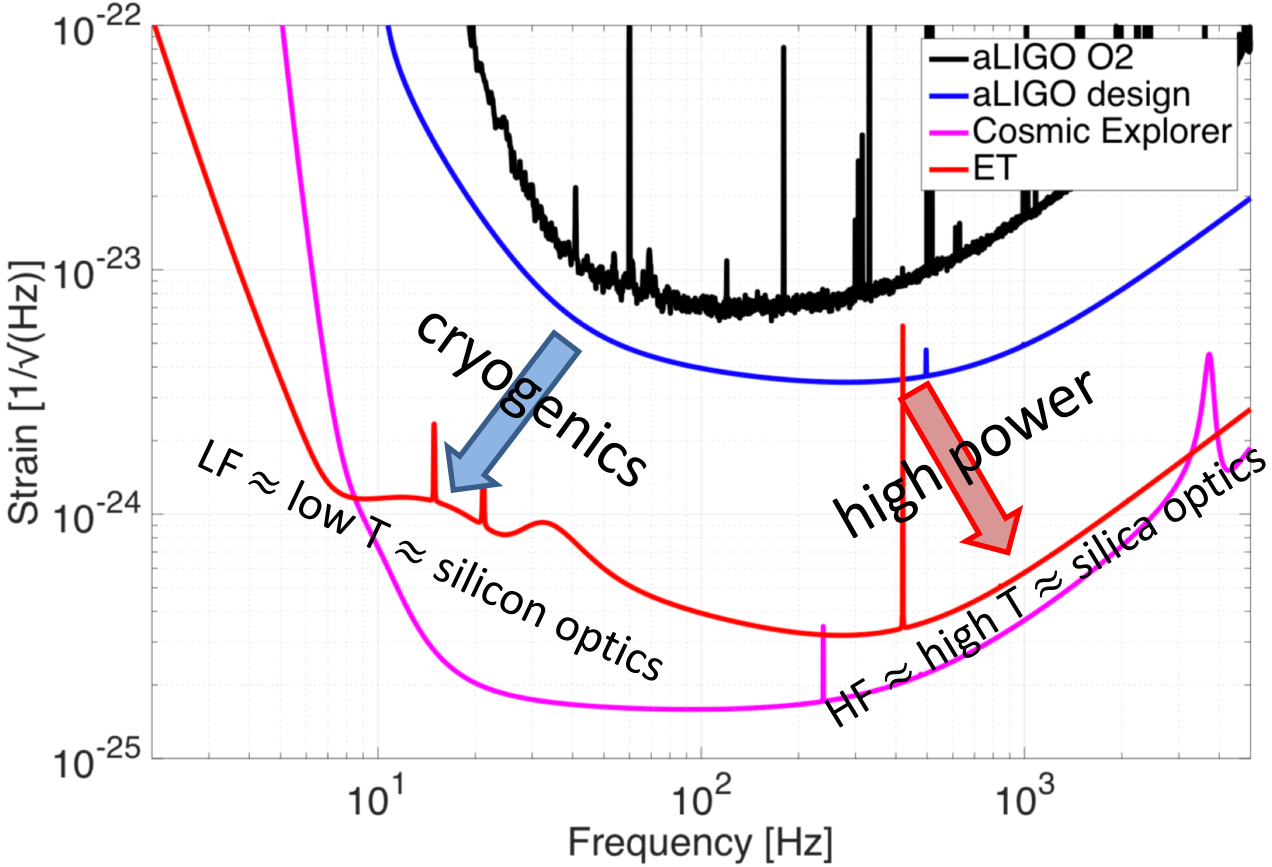
By Pallab Ghosh
Science correspondent, BBC News, Washington DC

15 February 2019



Factor 4 reduction in coating loss (factor 2 in strain noise) ~2020!

3G – xylophone concept

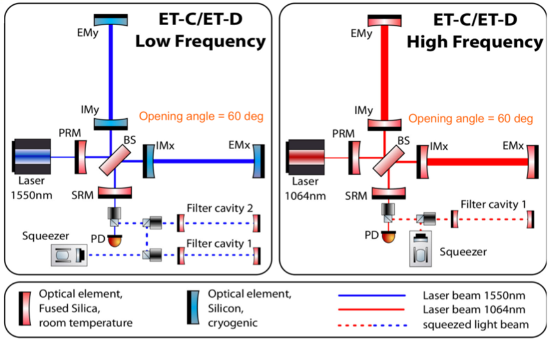


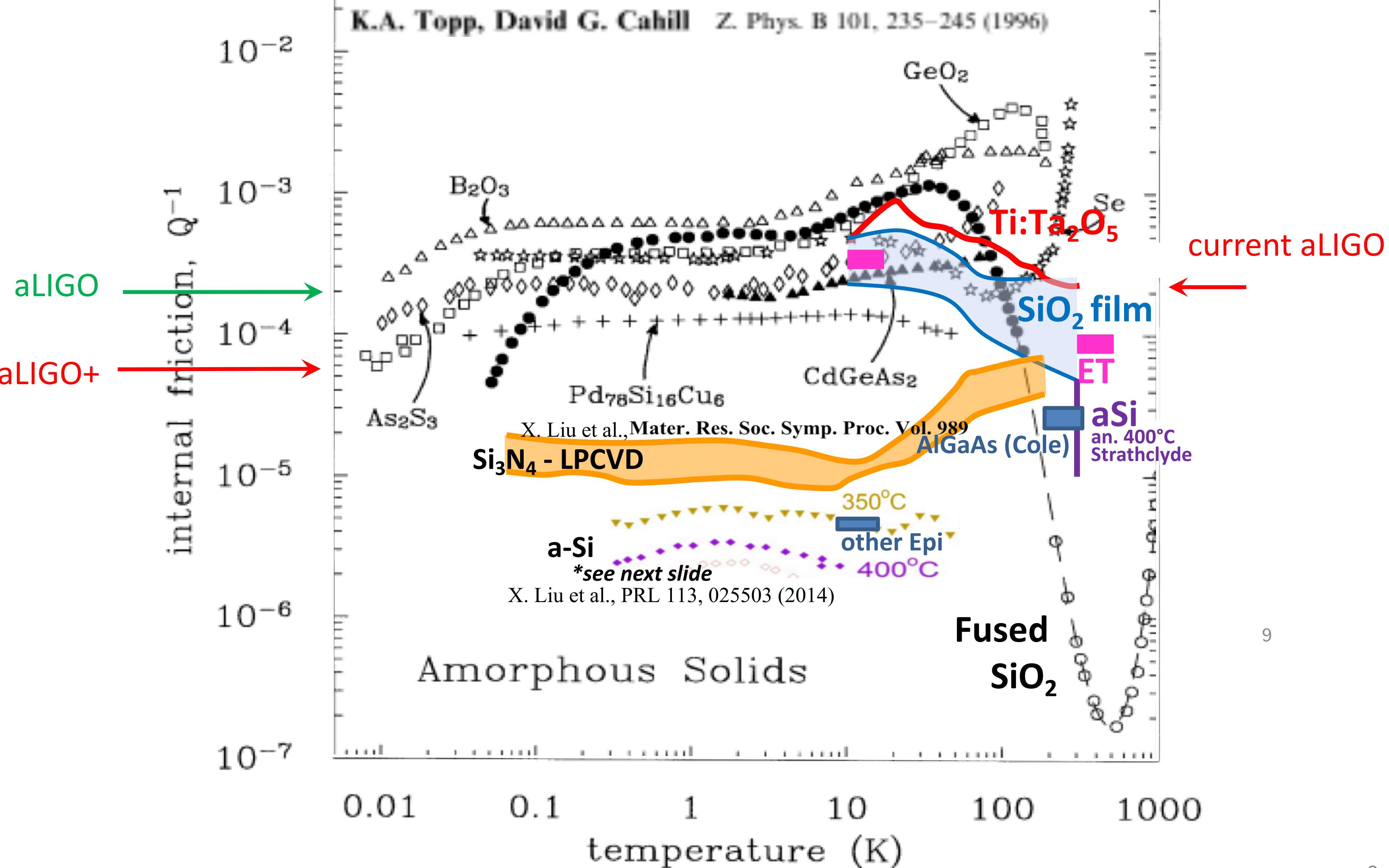
cryogenics

high power

LF ≈ low T ≈ silicon optics

HF ≈ high T ≈ silica optics

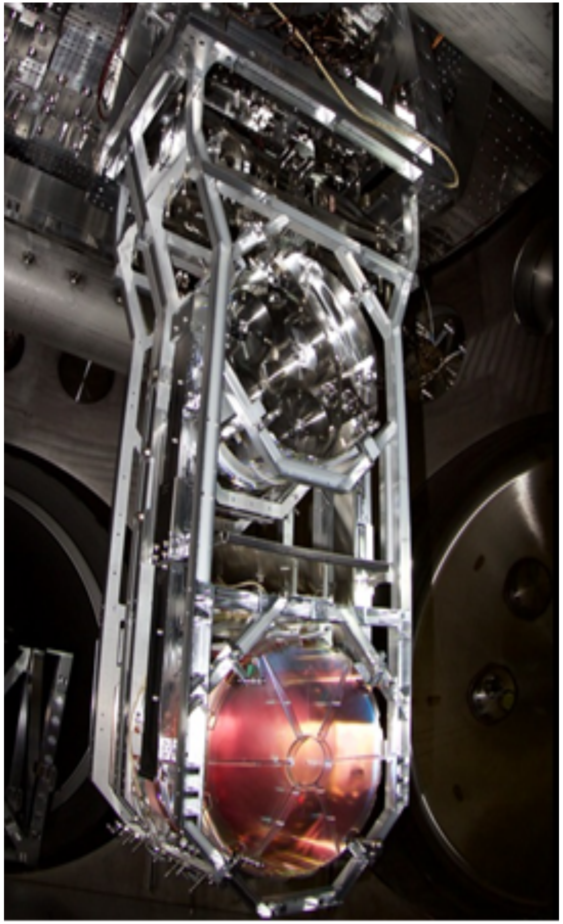


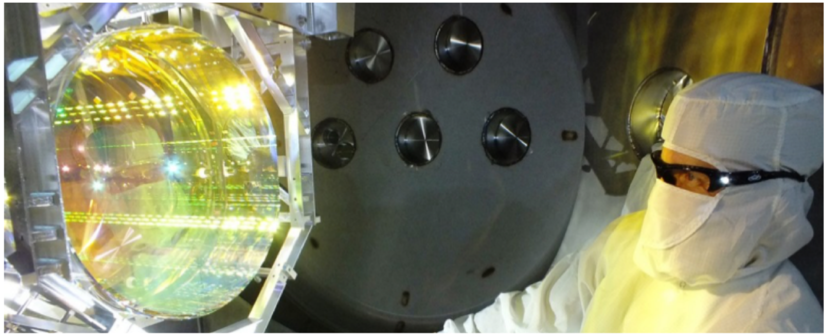

K.A. Topp, David G. Cahill Z. Phys. B 101, 235–245 (1996)
internal friction, Q^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
GeO₂
B₂O₃
Se
Ti:Ta₂O₅
current aLIGO
aLIGO
SiO₂ film
aLIGO+
CdGeAs₂
Pd₇₈Si₁₆Cu₆
As₂S₃
ET
aSi
an. 400°C
Strathclyde
X. Liu et al., Mater. Res. Soc. Symp. Proc. Vol. 989
Si₃N₄ - LPCVD
AlGaAs (Cole)
350°C
other Epi
a-Si
*see next slide
400°C
X. Liu et al., PRL 113, 025503 (2014)
Fused
SiO₂
Amorphous Solids
0.01
0.1
1
10
100
1000
temperature (K)

Advanced LIGO – mirror requirements

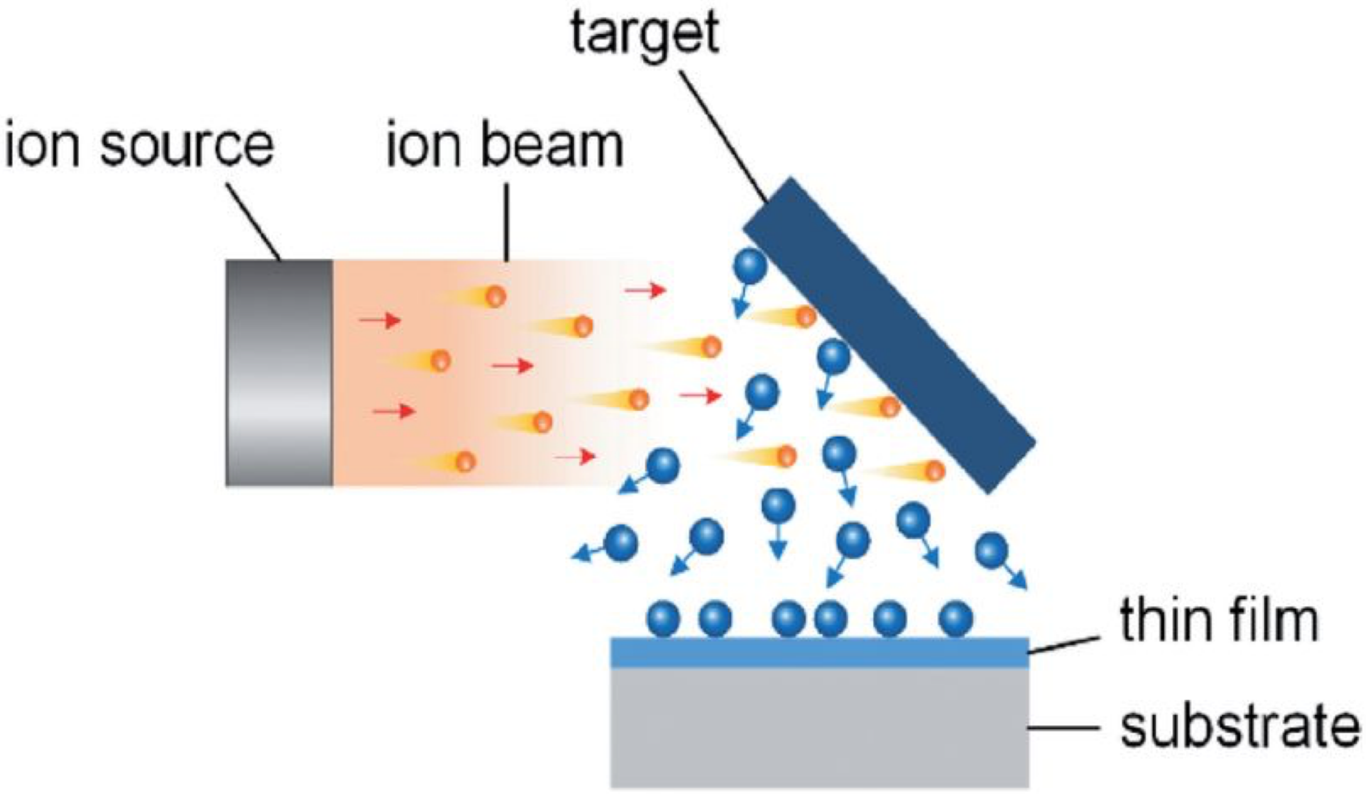
Requirements for aLIGO at 1064 nm:

- Absorption <0.5 ppm
- Scatter <2 ppm
- ITM transmission: $(5 \pm 0.25) \times 10^{-3}$
- ETM transmission: <10 ppm
- Mechanical loss: 3×10^{-5} Goal (1×10^{-4})
- Uniformity +/- 0.5% over 34 cm





Ion beam deposition (IBD)



Strategy for 3G – all (sensible) options open!

Reduced TN mirror coatings for + and 3G

Standard IBD – new/modified materials, alternative coating designs (e.g. mixed material, nanolayers,…), optimised post-annealing.

Modified IBD – extend dep parameter space (e.g. ion energy, dep rate, gas/materials), inclusion of assist processes?

MBE – switch to crystalline mirror coatings

other?!

Strategy for 3G – all (sensible) options open!

Reduced TN mirror coatings for + and 3G

Standard IBD – new/modified materials, alternative coating designs (e.g. mixed material, nanolayers,…), optimised post-annealing.

Benefit: *manufacture of mirrors unchanged, geometry/optical spec.* ✓

Risk: *two decades of research did not achieve factor 4 reduction in* ϕ*…*

Modified IBD – extend dep parameter space (*e.g.* ion energy, dep rate, gas/materials), inclusion of assist processes?

Benefit: *manufacture of mirrors similar, scalability prob OK*

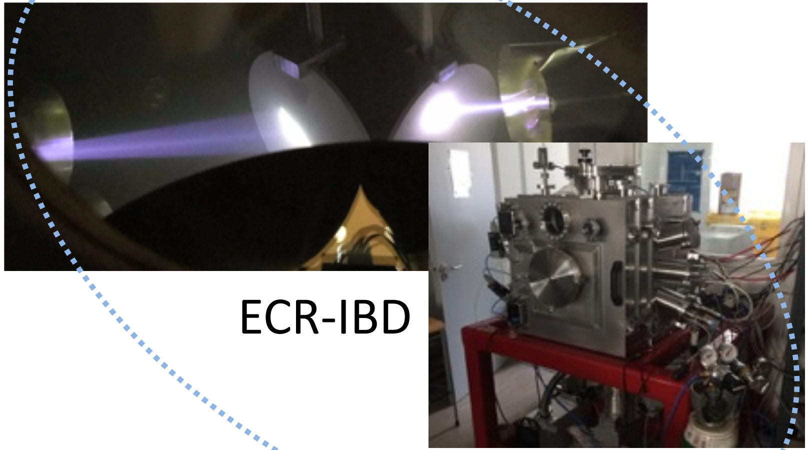
Risk: *no major industrial driver to support this approach – we need to do it!*

MBE – switch to crystalline mirror coatings

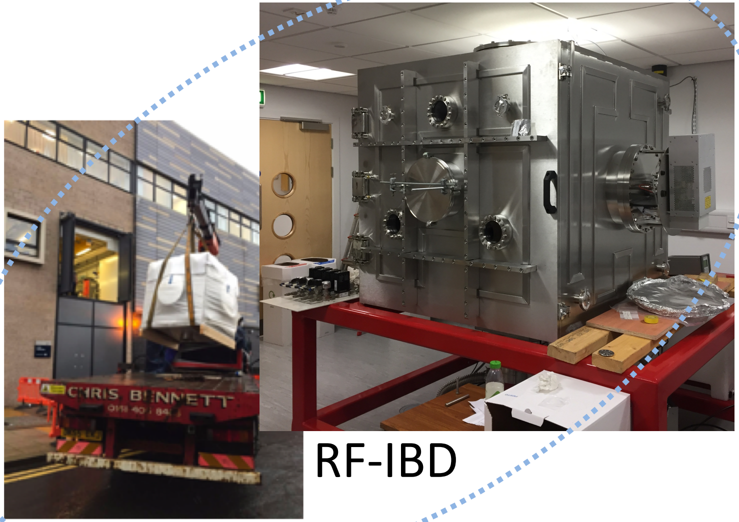
Benefit: *can satisfy optical and mechanical requirements easily*

Risk: *needs to be grown on lattice-matched substrate or transferred, area requires significant scaling (again industrial drivers unclear and are also commercially sensitive)*

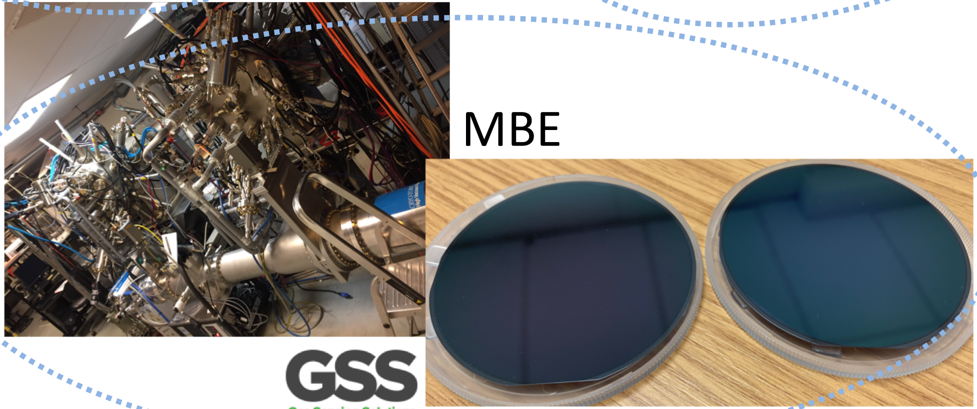
Coating technologies: ECR/RF IBD and MBE



ECR-IBD



RF-IBD



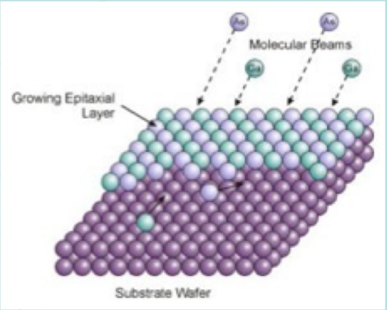
MBE

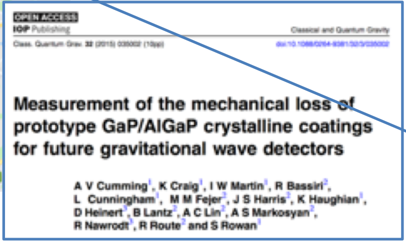
Coating technologies: ECR-IBD, RF-IBD and MBE

MBE – located in Gas Sensing Solutions

Crystalline coatings – possible 3rd generation solution:

P growths underway





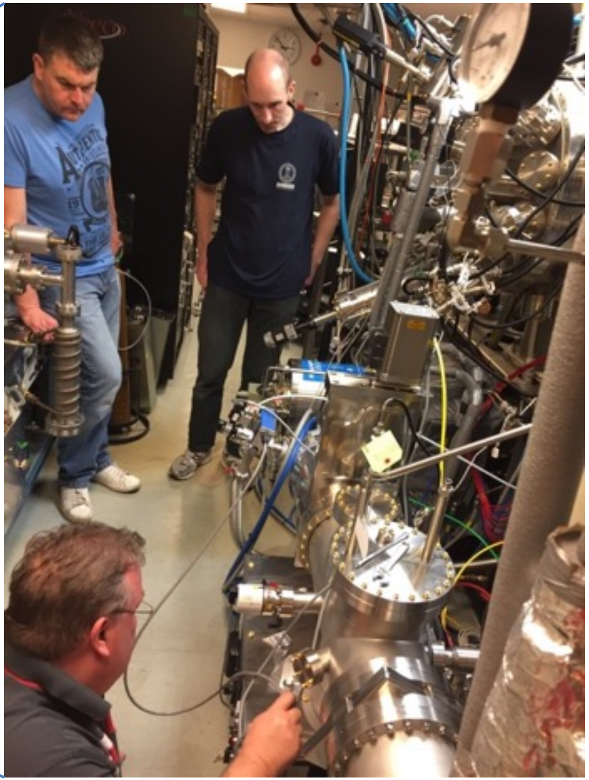
OPEN ACCESS

IOP Publishing — Classical and Quantum Gravity

Class. Quantum Grav. 32 (2015) 035002 (10pp) — doi:10.1088/0264-9381/32/3/035002

Measurement of the mechanical loss of prototype GaP/AlGaP crystalline coatings for future gravitational wave detectors

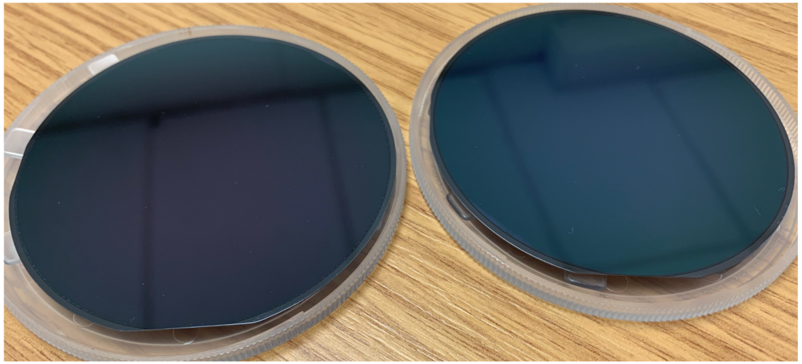
A V Cumming[1], K Craig[1], I W Martin[1], R Bassiri[2],
L Cunningham[1], M M Fejer[2], J S Harris[2], K Haughian[1],
D Heinert[3], B Lantz[2], A C Lin[2], A S Markosyan[2],
R Nawrodt[3], R Route[2] and S Rowan[1]



MBE – located in Gas Sensing Solutions

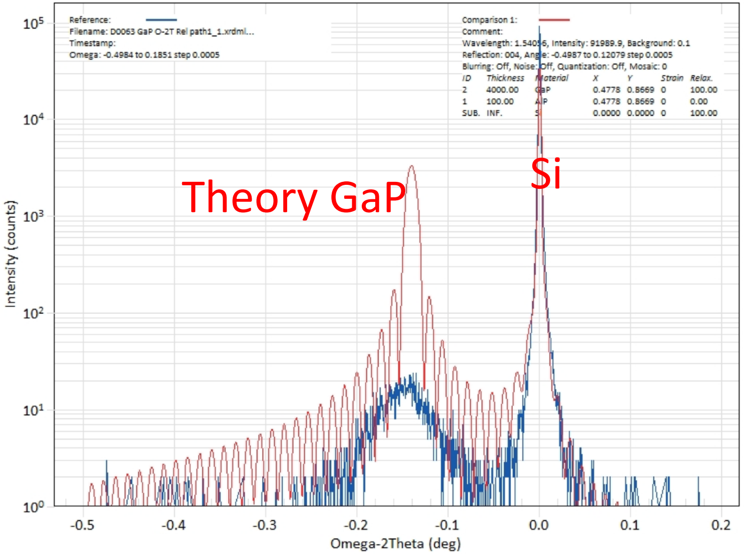
Crystalline coatings – possible 3rd generation solution:

P growths underway



300nm GaP coatings on Si

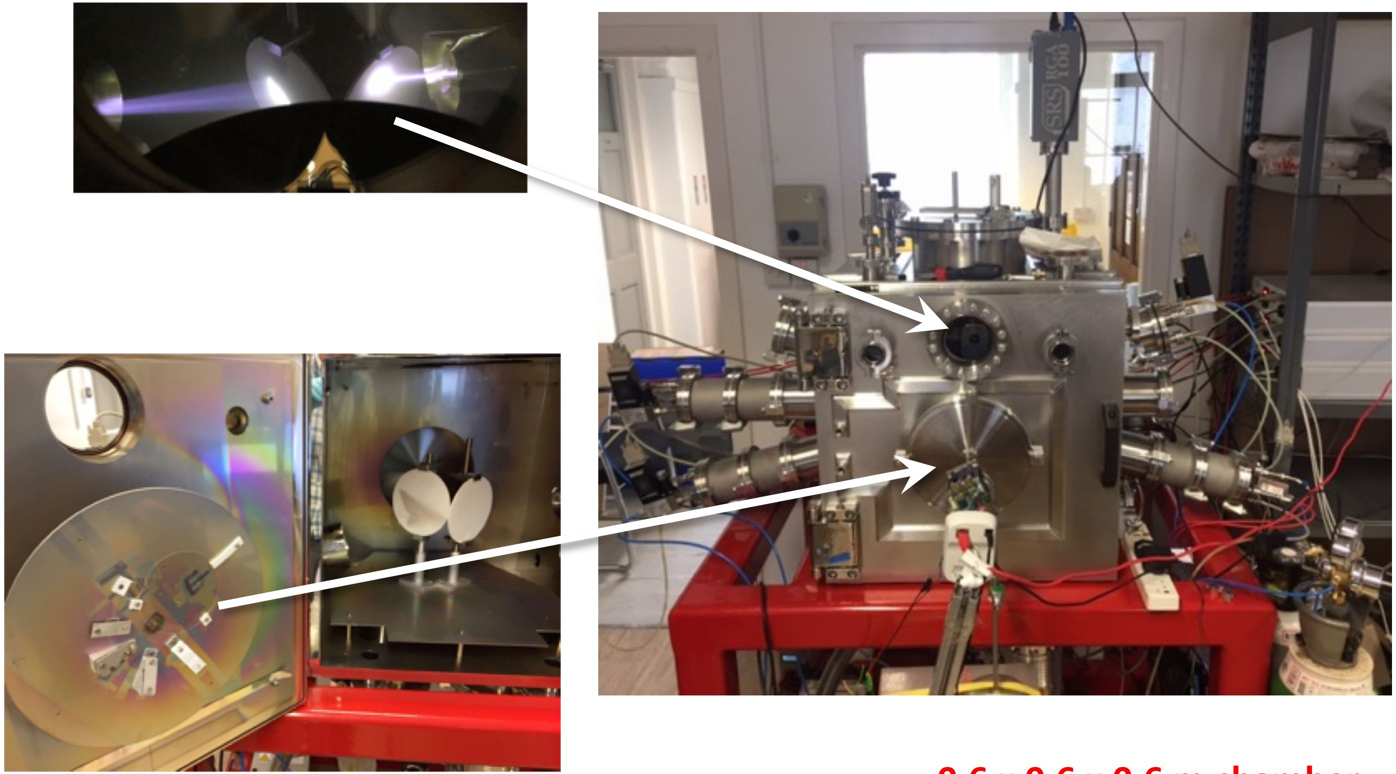
XRD



measured GaP

ECR plans

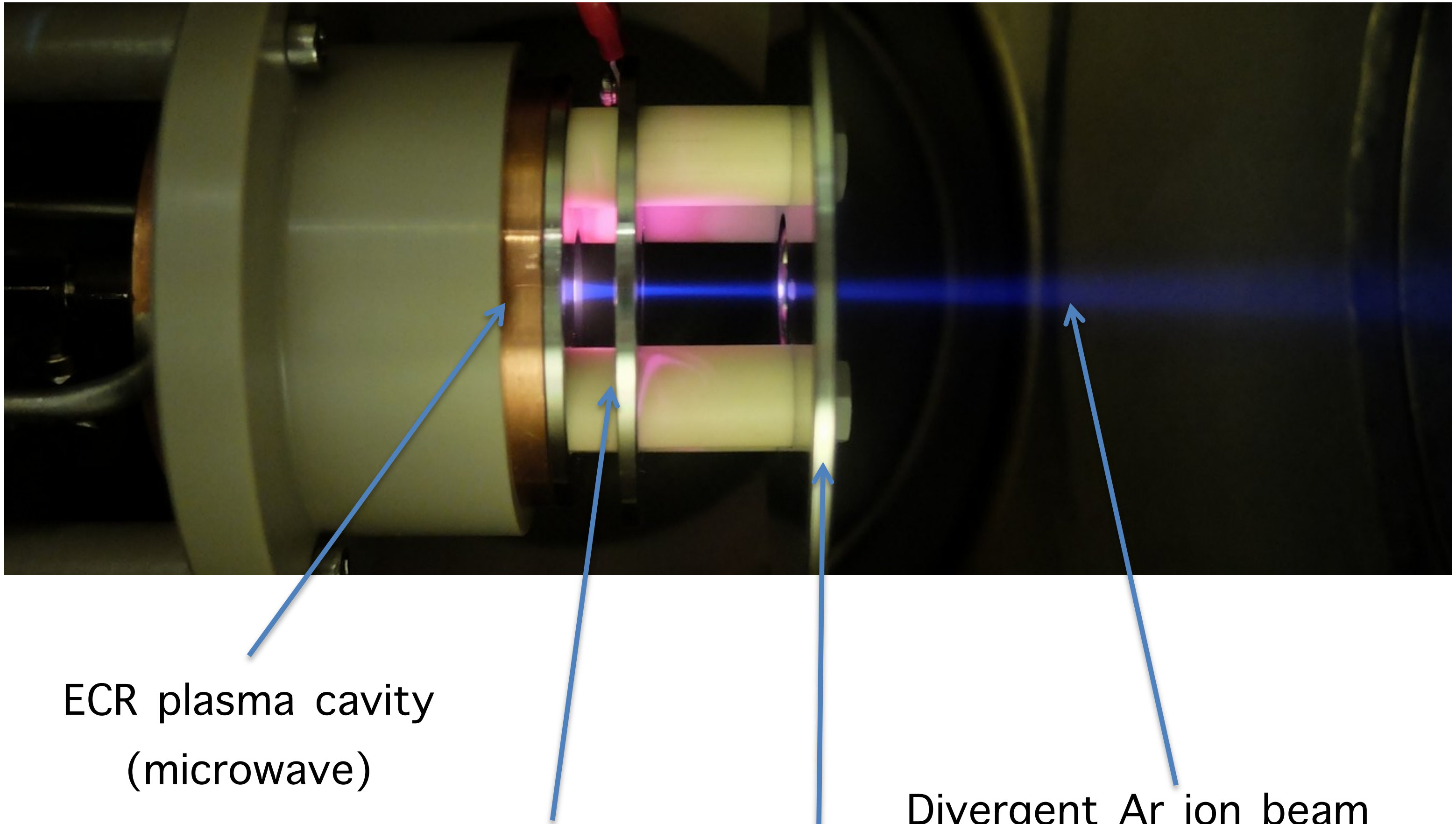
4 ion sources (soon 6 + 2 ECR plasma cavities) - independently controlled (LabView)



rotational staging – 14”

0.6 x 0.6 x 0.6 m chamber

Development of ECR-IBD



ECR plasma cavity (microwave)

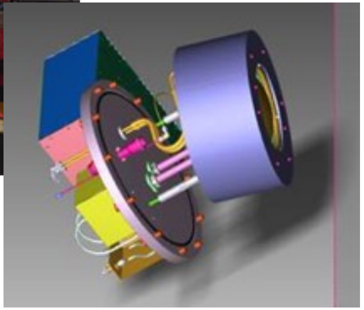
focus

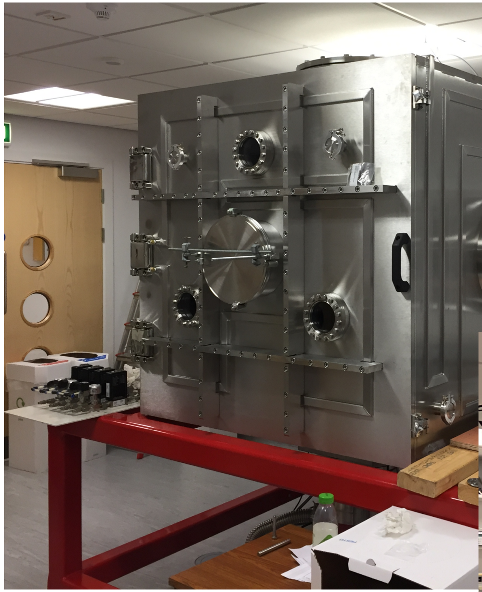
ground

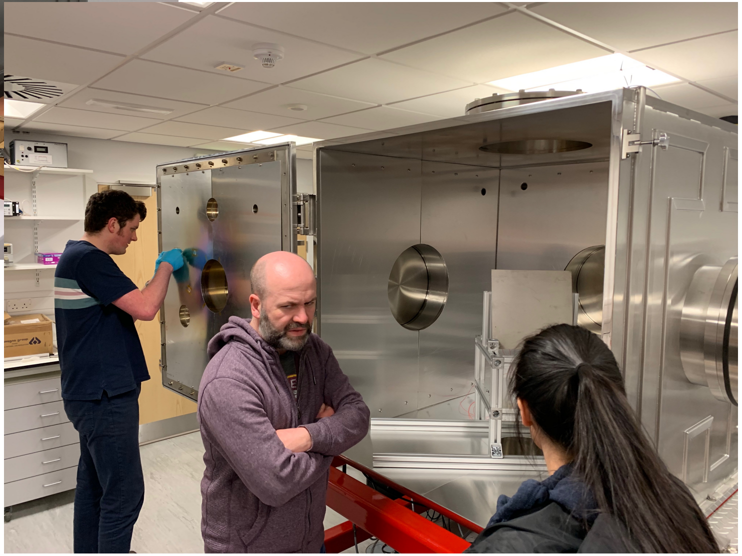
Divergent Ar ion beam

RF-IBD plans

1.2 x 1.2 x 1.2 m chamber



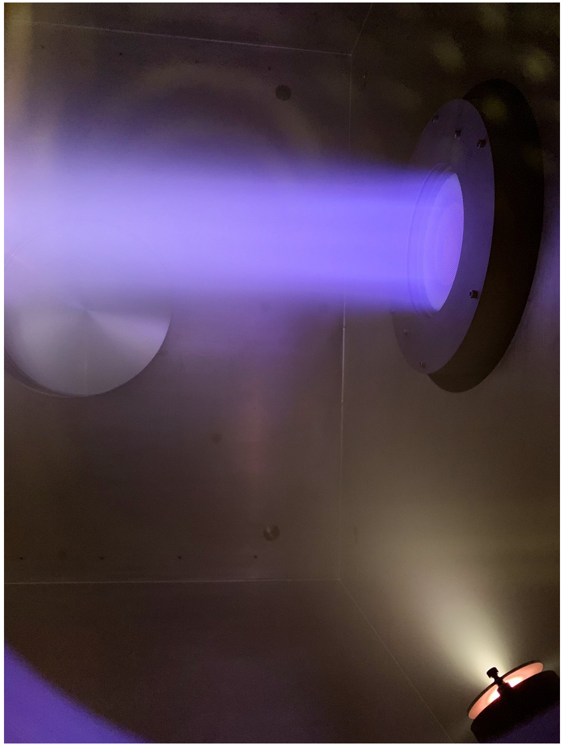


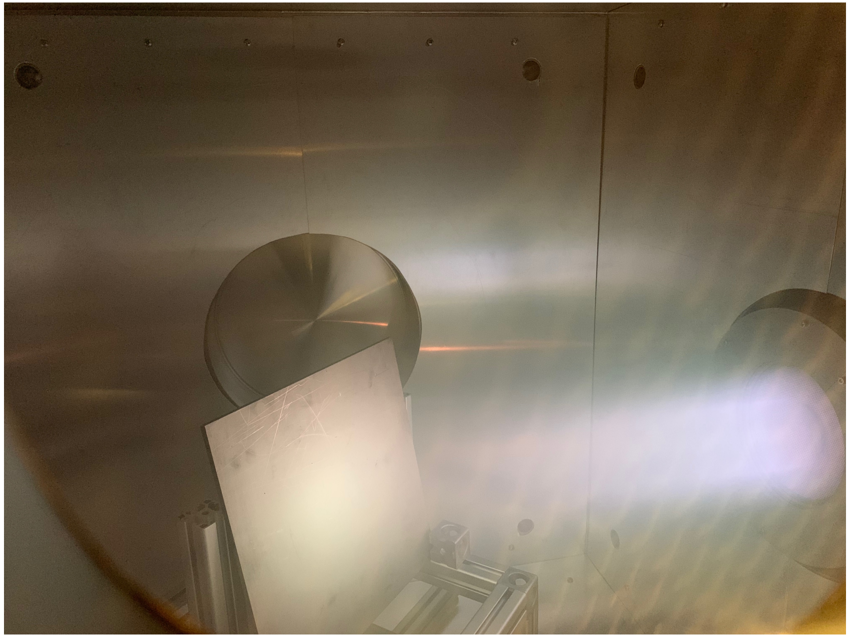


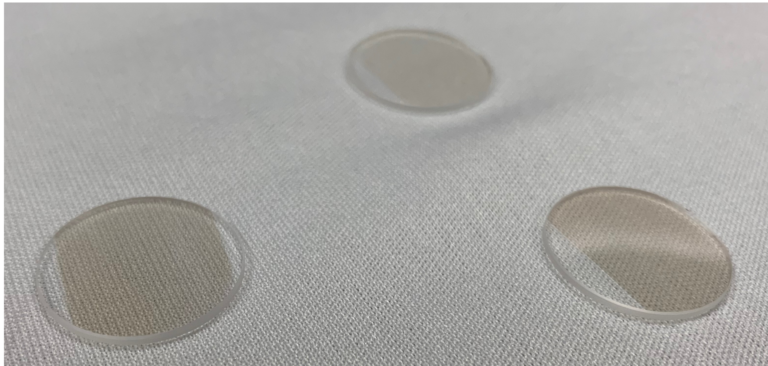
Industry standard 16” RF ion source (Veeco – Spector equivalent)

Any process developed in this system should be easily transferrable to e.g. LMA Grand Coater

RF-IBD plans





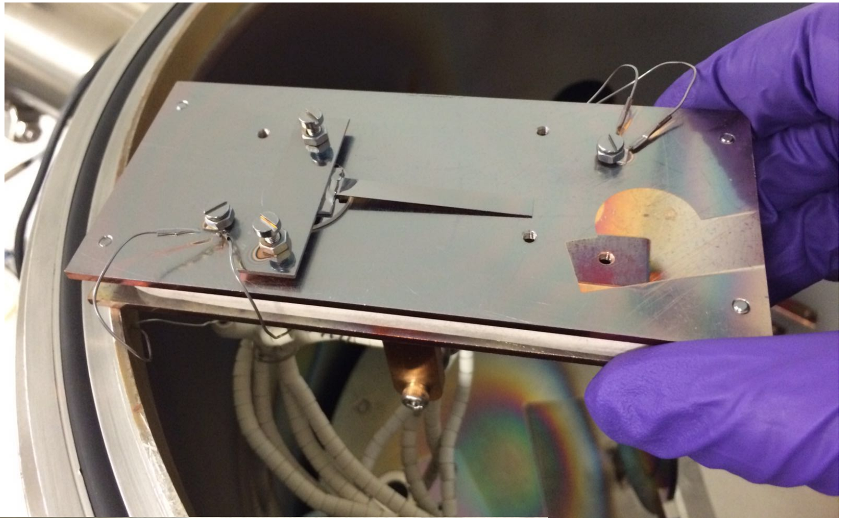


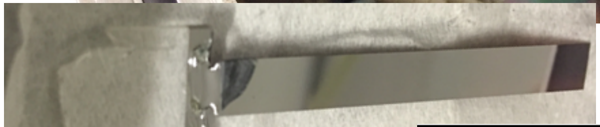
March 2019 first RF-ICP coating runs – TiO2

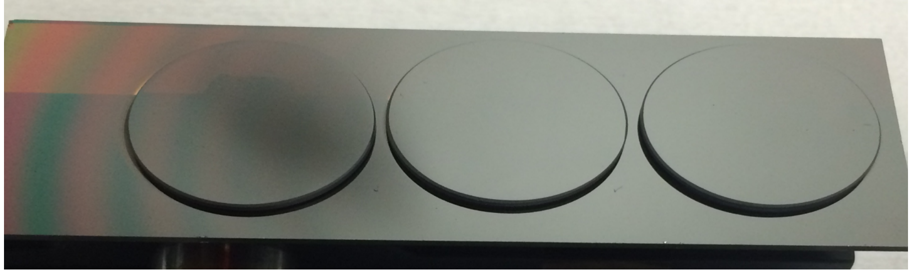
Amorphous silicon

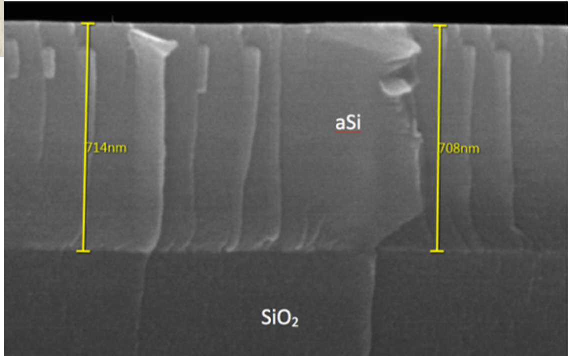
Copper mounting plate holds samples during deposition:

- SiO_2 cantilevers (mechanical loss)
- SiO_2 witness samples (optical studies)





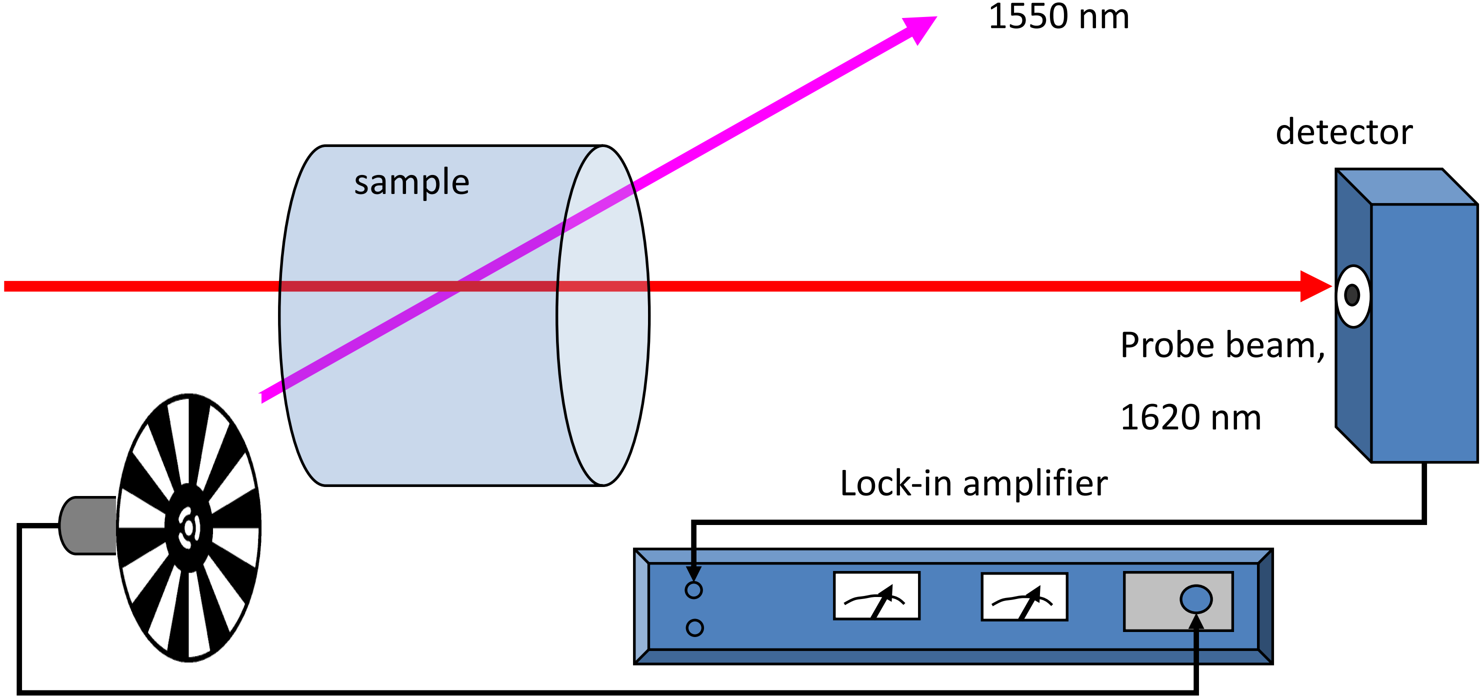




Absorption measurements - Glasgow

Photo-thermal commonpath interferometry (PCI)

A. Alexandrovski et al. *Proc. SPIE* 3610, Laser Material Crystal Growth and Nonlinear Materials and Devices, 44 (May 26, 1999);



Slides courtesy of J. Steinlechner (IGR, Glasgow)

Absorption measurements - Glasgow

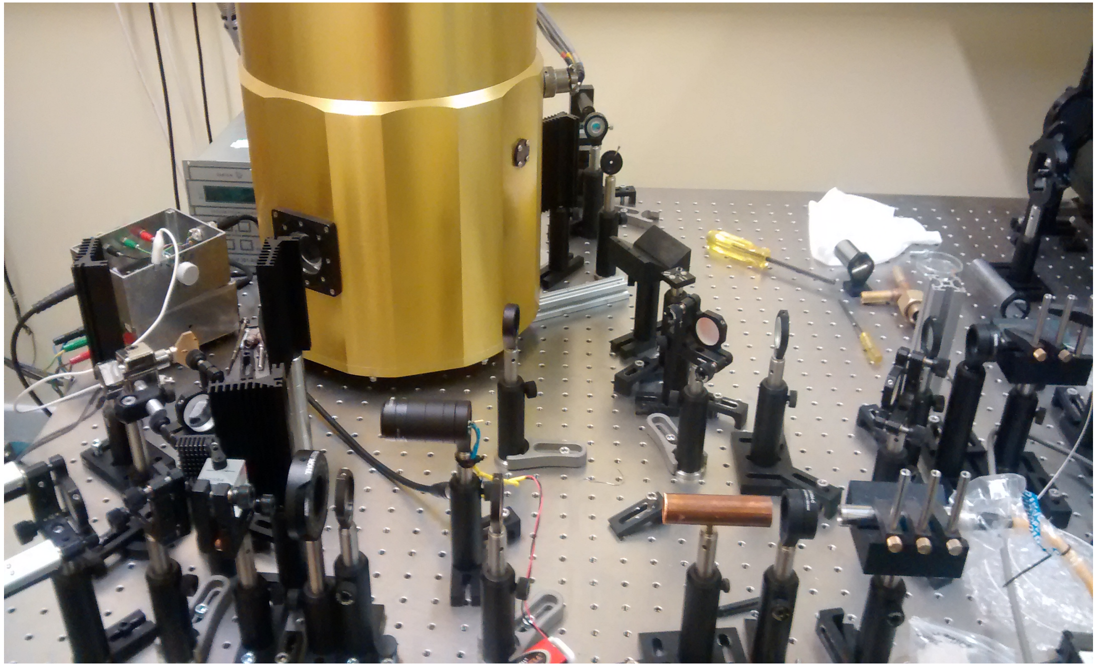
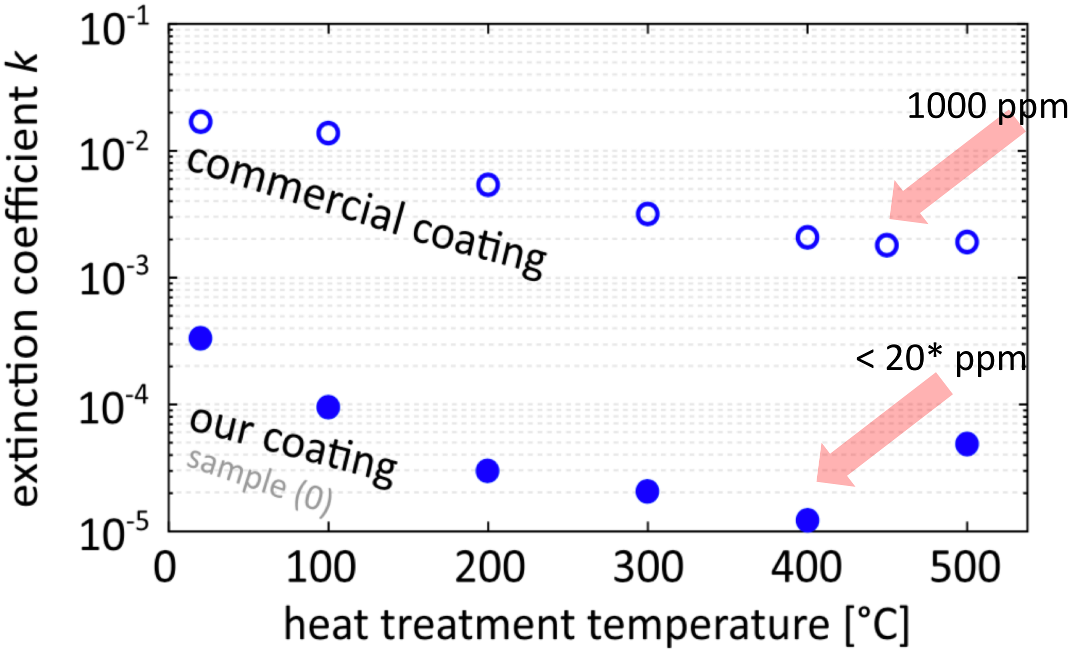


Figure 5 - photothermal absorption set up in UoG, capable of measuring ppm-level absorption in optical coatings

aSi Absorption – 1550nm



- 1550 nm
- Absorption significantly lower than for ATF coatings
- Refractive index ~3.4 from transmission measurements

* Measurements limited by absorption of substrate

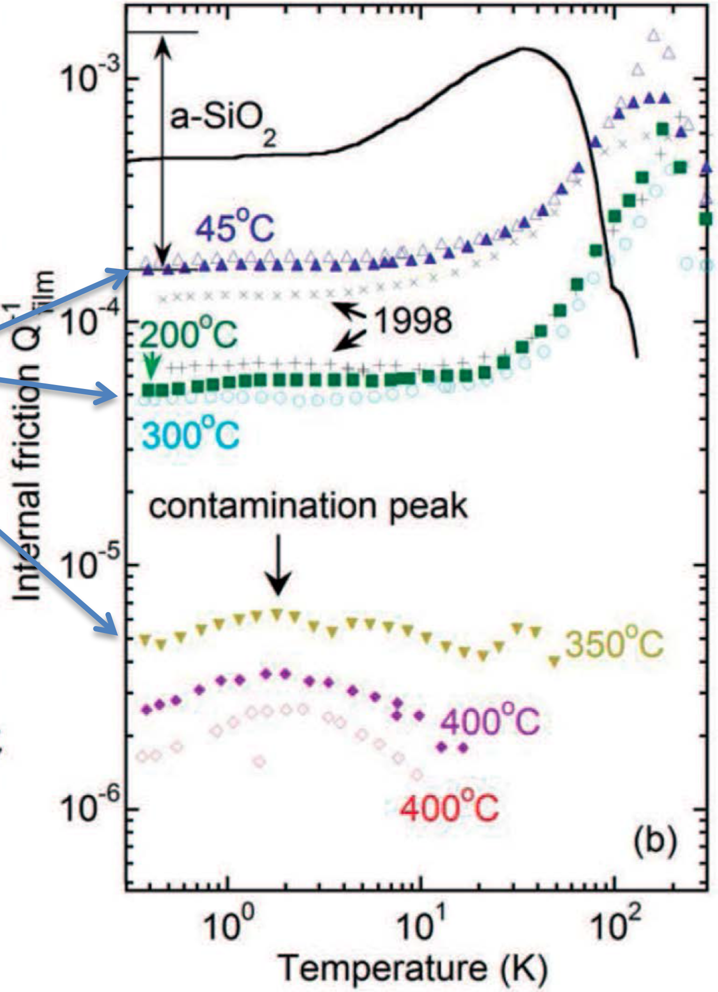
Other attractive solutions – elevated T dep.

- Significant interest in “ideal glass” structure
- Heated deposition reduces mechanical loss much further than post- heat treatment alone.

annealed 350C

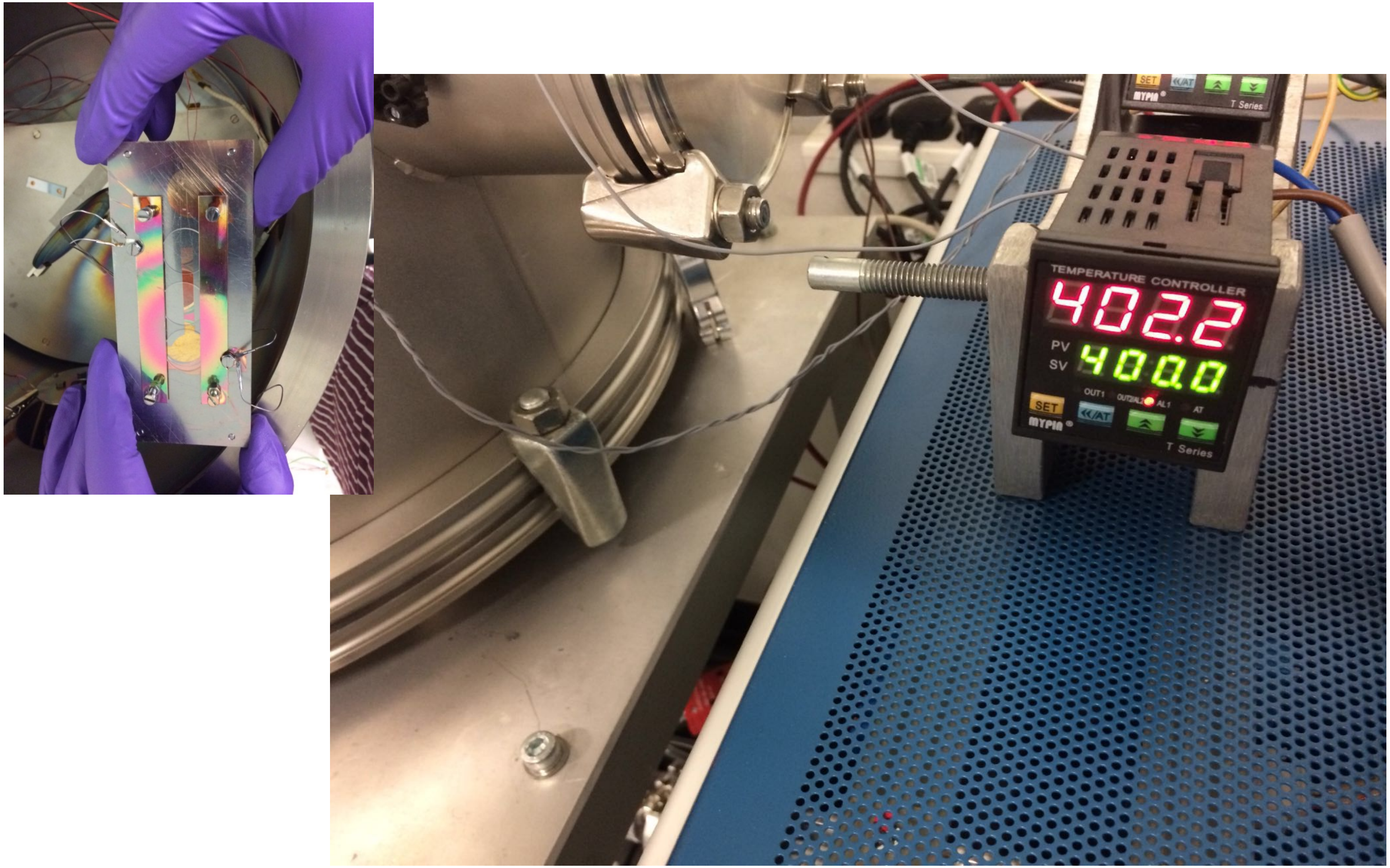
deposited 350C

- ~10^{-4} vs ~10^{-6}
- Surface mobility during deposition:
  - sound velocity approaches asymptote
  - distribution of bond angles narrows
  - density increasing
  - Heat capacity approaches bulk silicon value
- Open question – similar benefits for IBS?

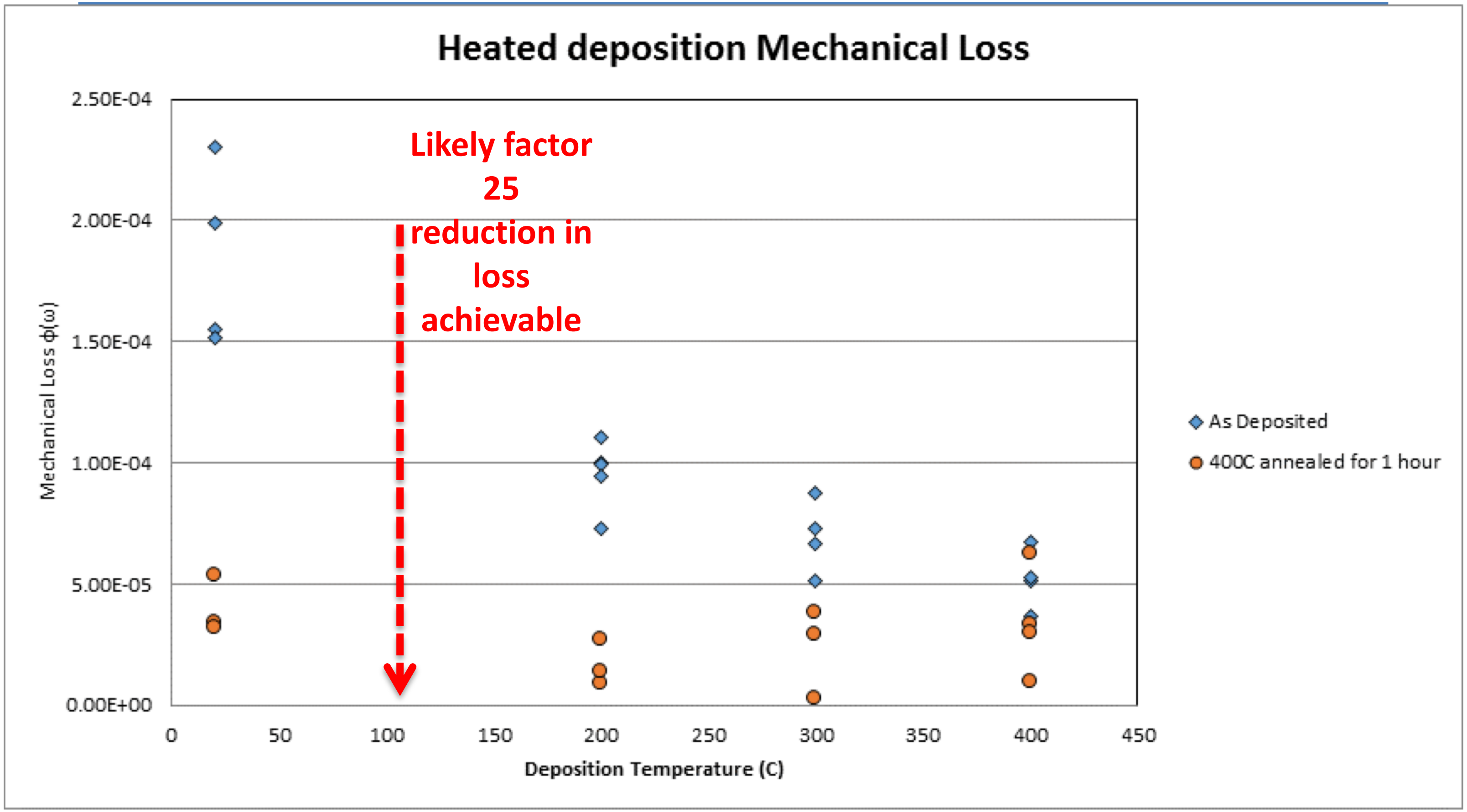


X. Liu, F. Hellman, et al, *PRL* **113**, 025503 (2014)

High-temperature deposition

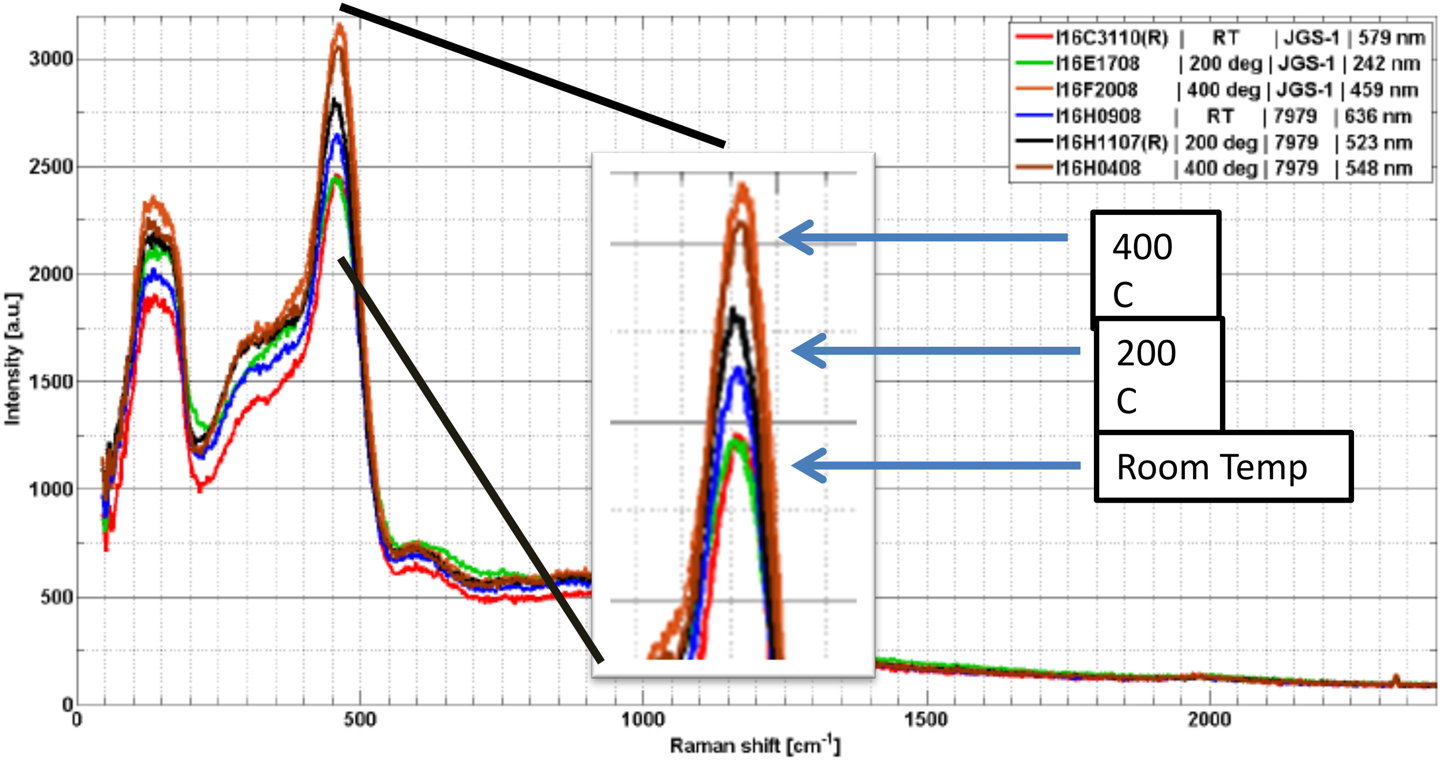


aSi Heated deposition losses



Likely factor 25 reduction in loss achievable

Characterisation – Raman

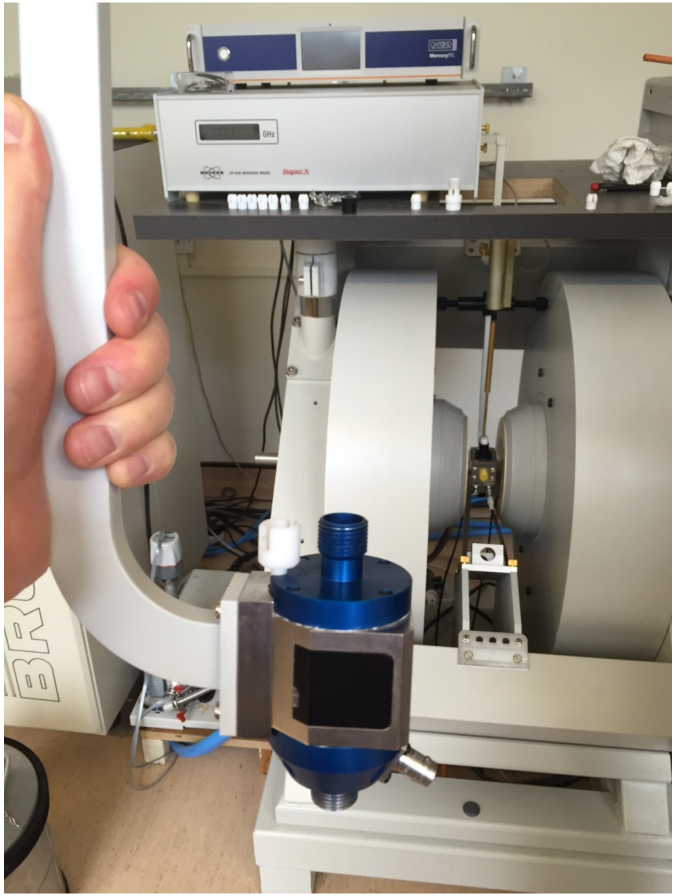


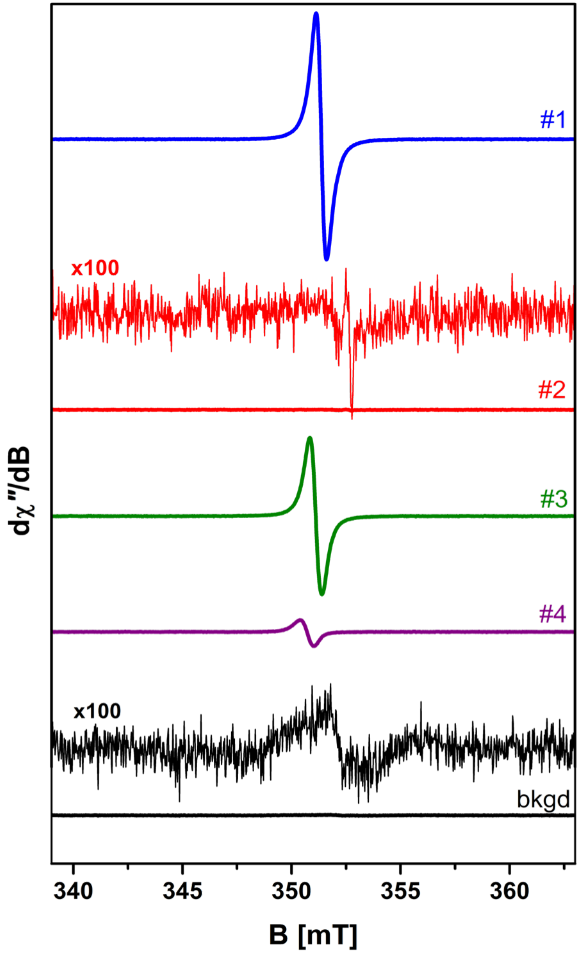
400 C

200 C

Room Temp

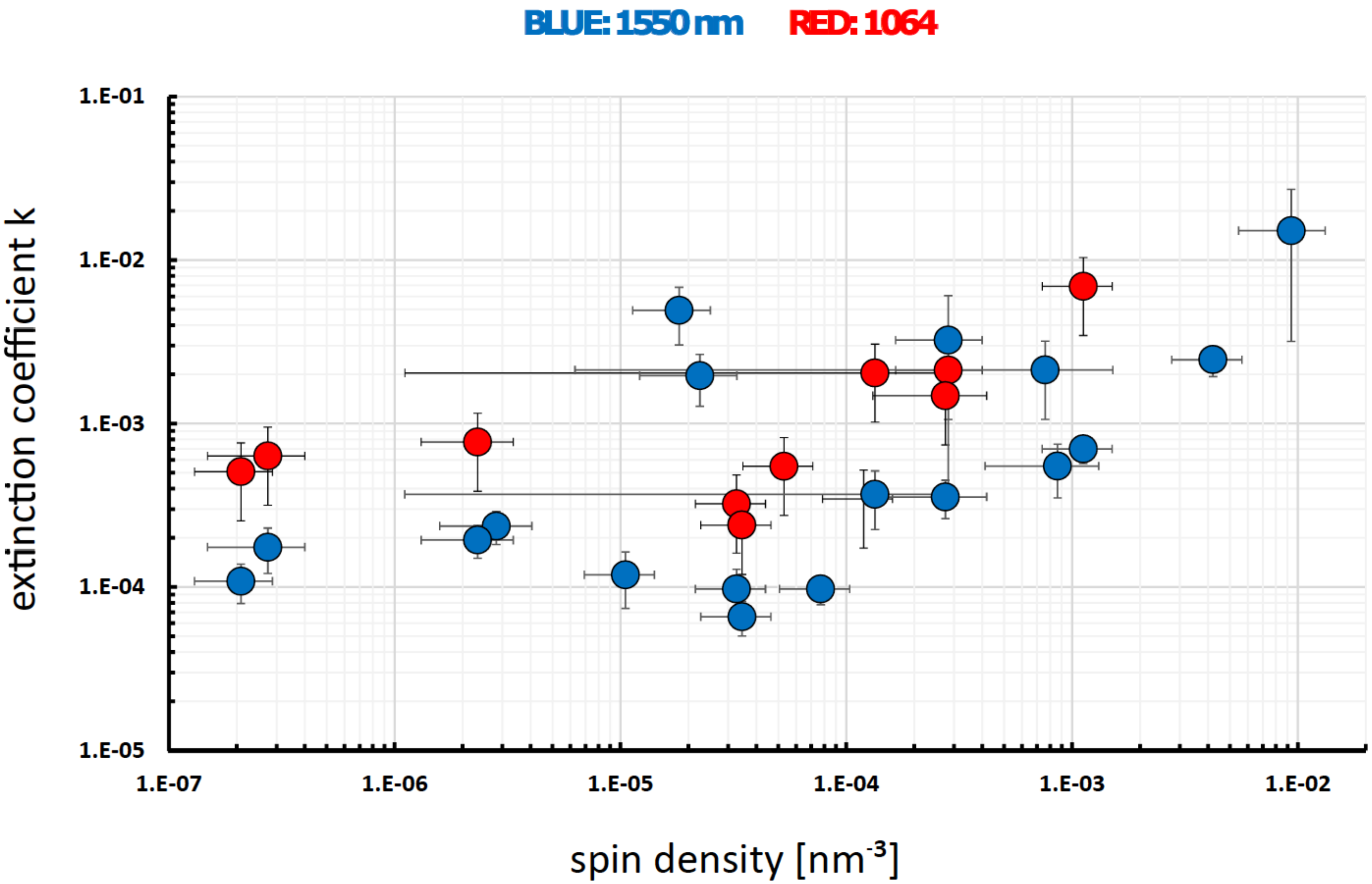
Characterisation – EPR



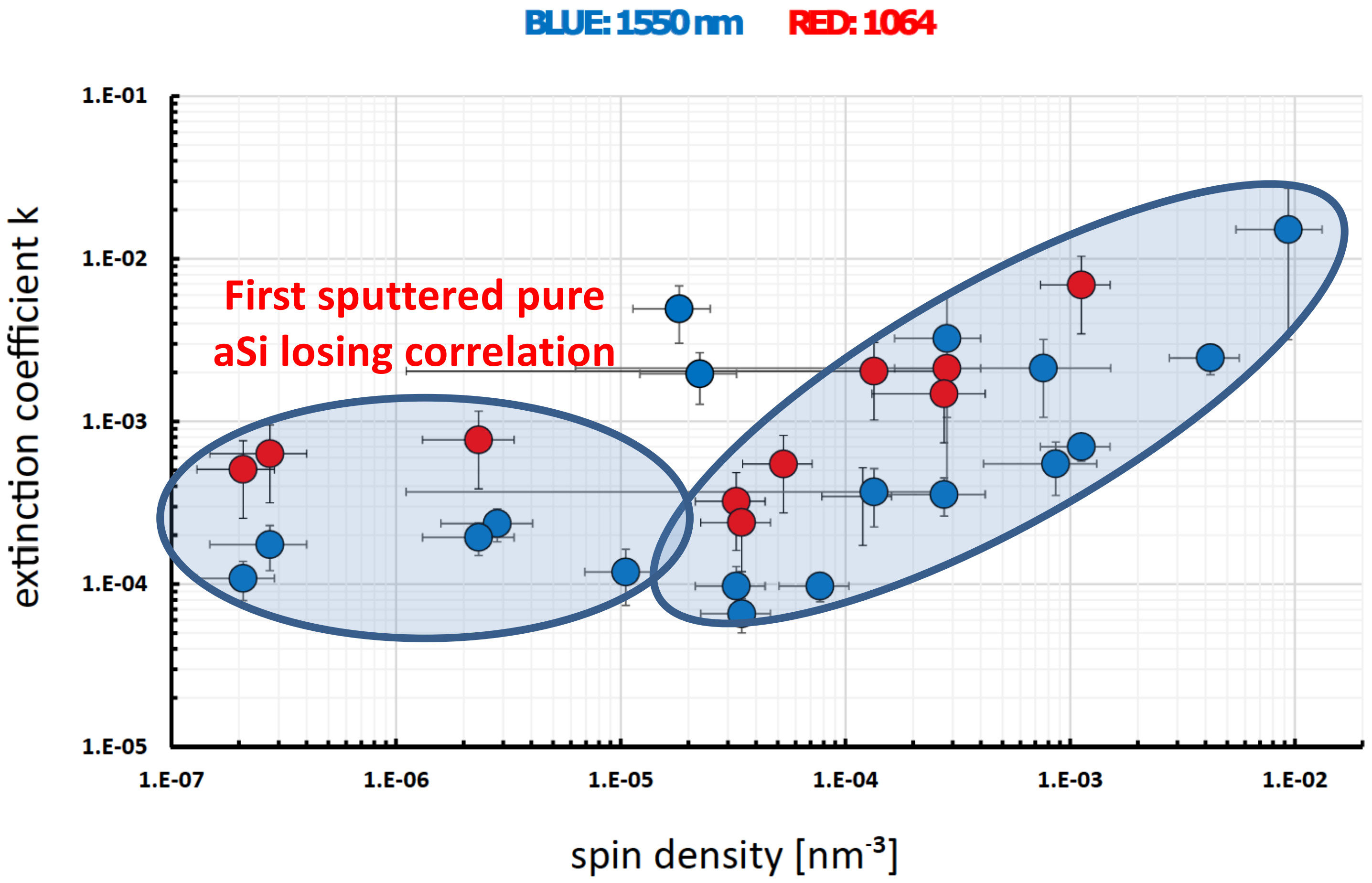


Electron paramagnetic resonance

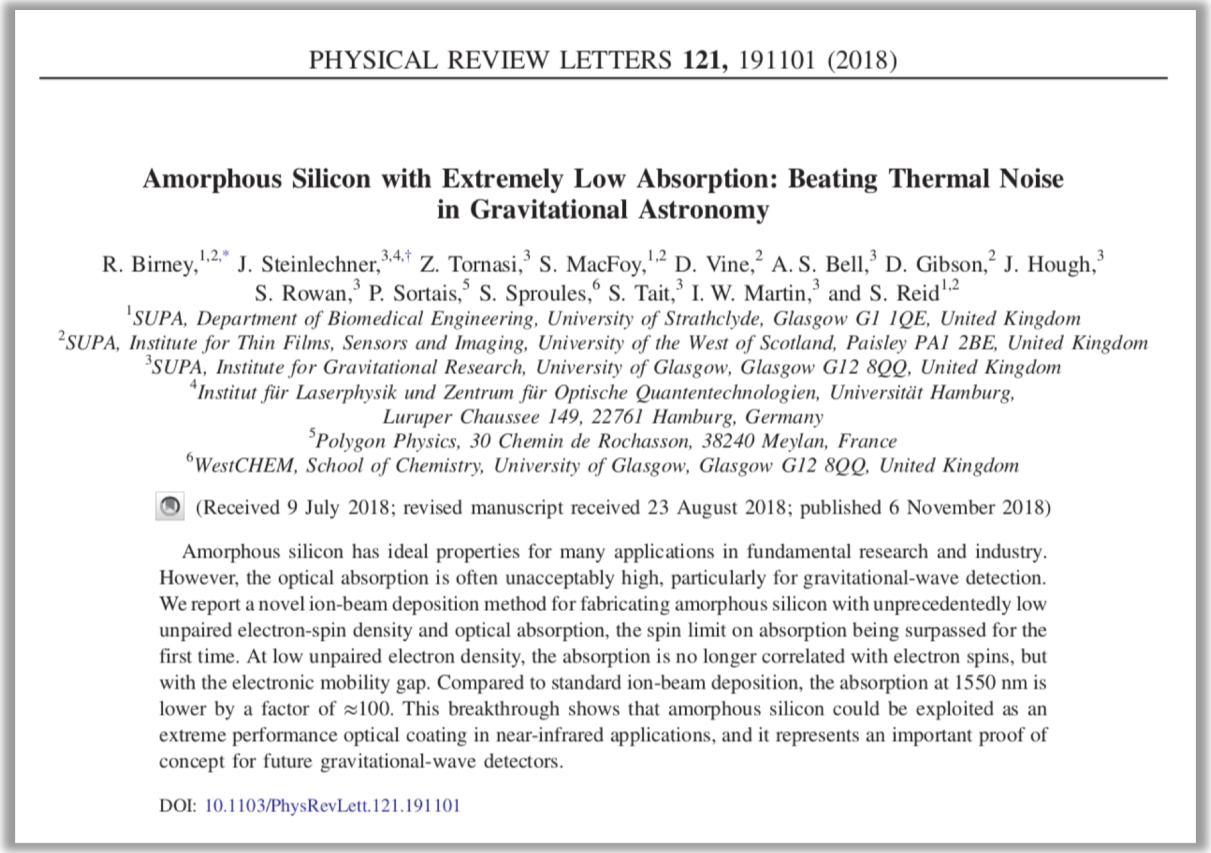
Dangling bond correlation with absorption



Dangling bond correlation with absorption



Dangling bond correlation with absorption



PHYSICAL REVIEW LETTERS **121,** 191101 (2018)

Amorphous Silicon with Extremely Low Absorption: Beating Thermal Noise in Gravitational Astronomy

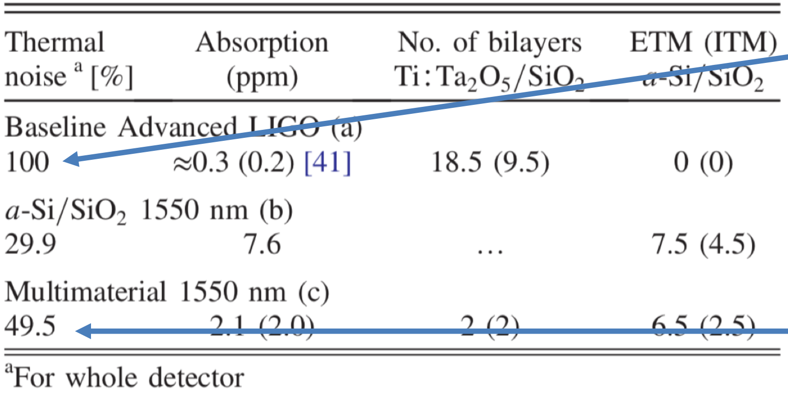
R. Birney,[1,2,*] J. Steinlechner,[3,4,†] Z. Tornasi,[3] S. MacFoy,[1,2] D. Vine,[2] A. S. Bell,[3] D. Gibson,[2] J. Hough,[3]
S. Rowan,[3] P. Sortais,[5] S. Sproules,[6] S. Tait,[3] I. W. Martin,[3] and S. Reid[1,2]
[1]*SUPA, Department of Biomedical Engineering, University of Strathclyde, Glasgow G1 1QE, United Kingdom*
[2]*SUPA, Institute for Thin Films, Sensors and Imaging, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[3]*SUPA, Institute for Gravitational Research, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[4]*Institut für Laserphysik und Zentrum für Optische Quantentechnologien, Universität Hamburg,*
Luruper Chaussee 149, 22761 Hamburg, Germany
[5]*Polygon Physics, 30 Chemin de Rochasson, 38240 Meylan, France*
[6]*WestCHEM, School of Chemistry, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

(Received 9 July 2018; revised manuscript received 23 August 2018; published 6 November 2018)

Amorphous silicon has ideal properties for many applications in fundamental research and industry. However, the optical absorption is often unacceptably high, particularly for gravitational-wave detection. We report a novel ion-beam deposition method for fabricating amorphous silicon with unprecedentedly low unpaired electron-spin density and optical absorption, the spin limit on absorption being surpassed for the first time. At low unpaired electron density, the absorption is no longer correlated with electron spins, but with the electronic mobility gap. Compared to standard ion-beam deposition, the absorption at 1550 nm is lower by a factor of ≈100. This breakthrough shows that amorphous silicon could be exploited as an extreme performance optical coating in near-infrared applications, and it represents an important proof of concept for future gravitational-wave detectors.

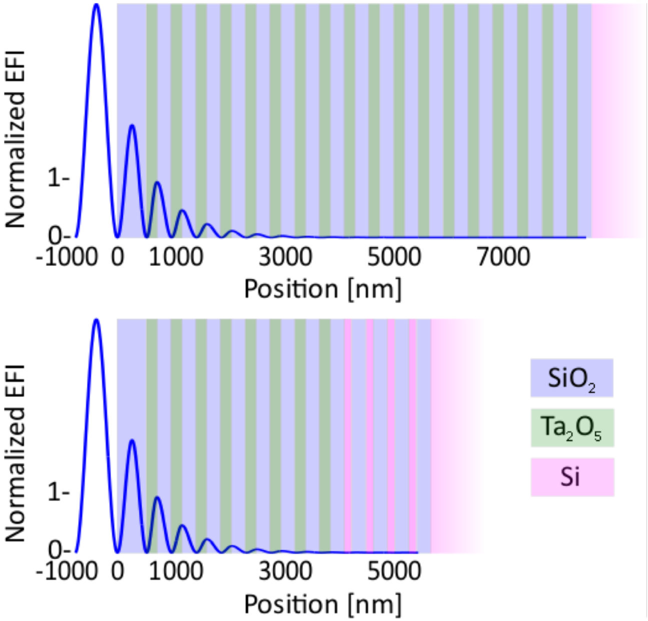
DOI: 10.1103/PhysRevLett.121.191101

Thermal noise

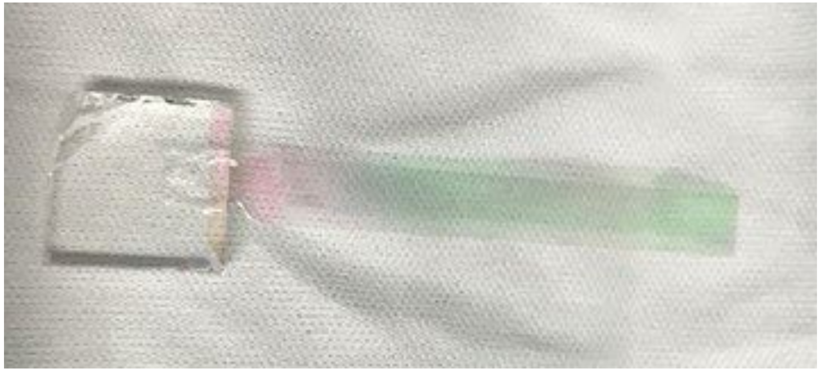


Thermal noise [a] [%]	Absorption (ppm)	No. of bilayers Ti:Ta_2O_5/SiO_2	ETM (ITM) a-Si/SiO_2
Baseline Advanced LIGO (a)			
100	≈0.3 (0.2) [41]	18.5 (9.5)	0 (0)
a-Si/SiO_2 1550 nm (b)			
29.9	7.6	…	7.5 (4.5)
Multimaterial 1550 nm (c)			
49.5	2.1 (2.0)	2 (2)	6.5 (2.5)

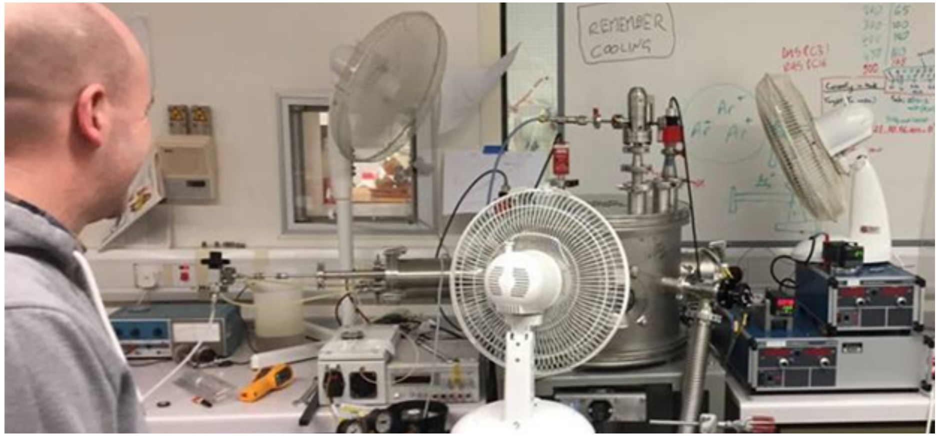
[a] For whole detector



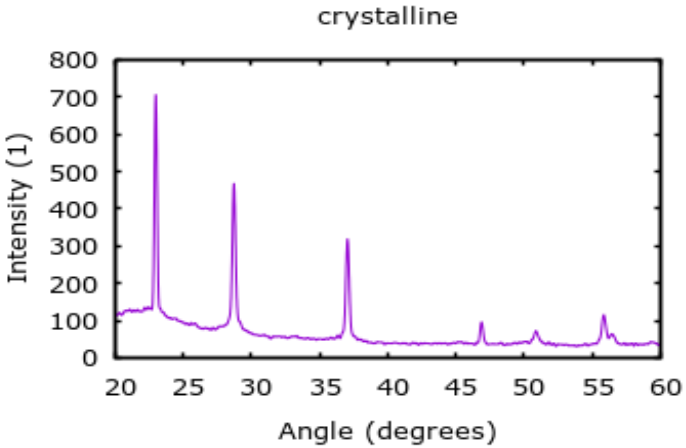
High temp deposition of tantala (Ta_2O_5)



Deposition temperatures up to 500C with some “effort”



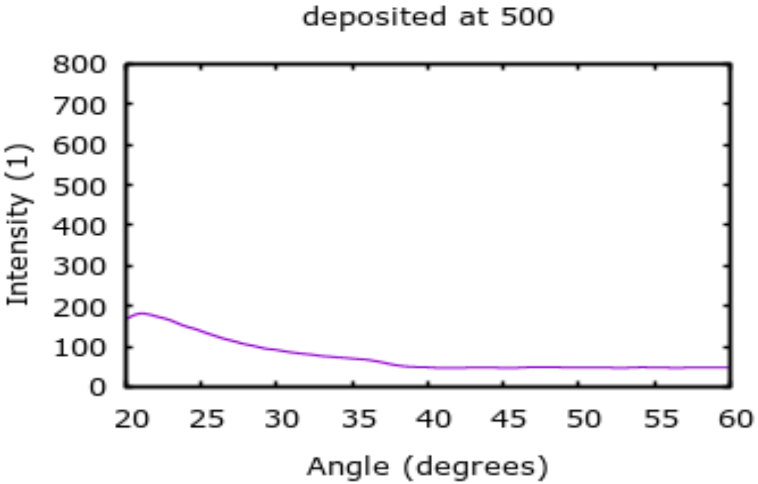
Tantala XRD



Sample of tantala deposited at 300C

Annealed at 700C for 5 hours.

Crystalline features shown

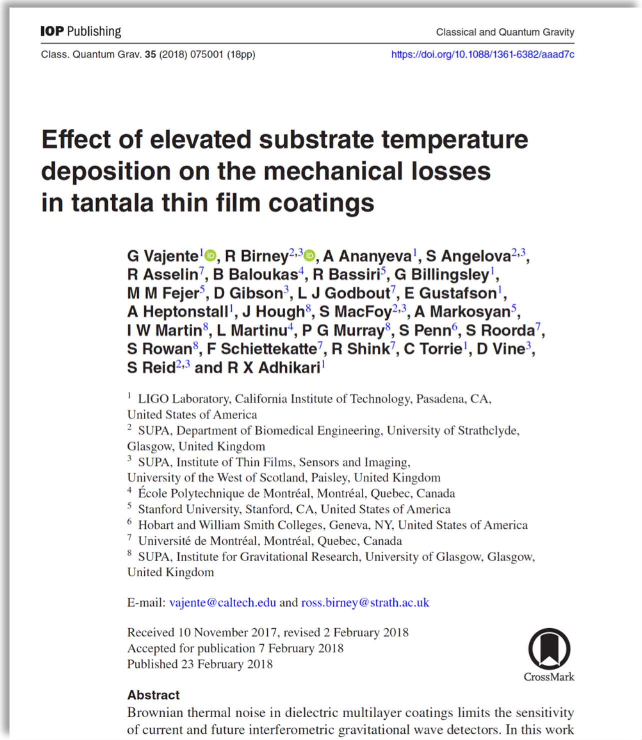


Sample of tantala deposited at 500C

Not annealed yet

Shows no crystalline features

Tantala Mechanical Loss



IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. **35** (2018) 075001 (18pp) https://doi.org/10.1088/1361-6382/aaad7c

Effect of elevated substrate temperature deposition on the mechanical losses in tantala thin film coatings

G Vajente[1], R Birney[2,3], A Ananyeva[1], S Angelova[2,3], R Asselin[7], B Baloukas[4], R Bassiri[5], G Billingsley[1], M M Fejer[5], D Gibson[3], L J Godbout[7], E Gustafson[1], A Heptonstall[1], J Hough[8], S MacFoy[2,3], A Markosyan[5], I W Martin[8], L Martinu[4], P G Murray[8], S Penn[6], S Roorda[7], S Rowan[8], F Schiettekatte[7], R Shink[7], C Torrie[1], D Vine[3], S Reid[2,3] and R X Adhikari[1]

[1] LIGO Laboratory, California Institute of Technology, Pasadena, CA, United States of America
[2] SUPA, Department of Biomedical Engineering, University of Strathclyde, Glasgow, United Kingdom
[3] SUPA, Institute of Thin Films, Sensors and Imaging, University of the West of Scotland, Paisley, United Kingdom
[4] École Polytechnique de Montréal, Montréal, Quebec, Canada
[5] Stanford University, Stanford, CA, United States of America
[6] Hobart and William Smith Colleges, Geneva, NY, United States of America
[7] Université de Montréal, Montréal, Quebec, Canada
[8] SUPA, Institute for Gravitational Research, University of Glasgow, Glasgow, United Kingdom

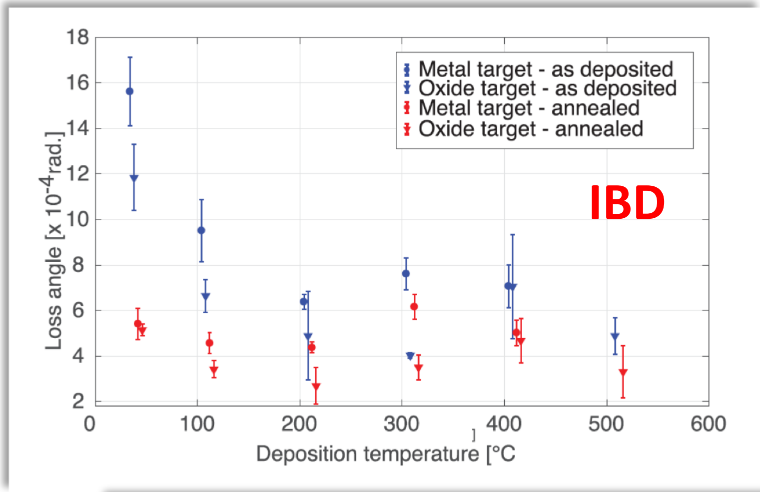
E-mail: vajente@caltech.edu and ross.birney@strath.ac.uk

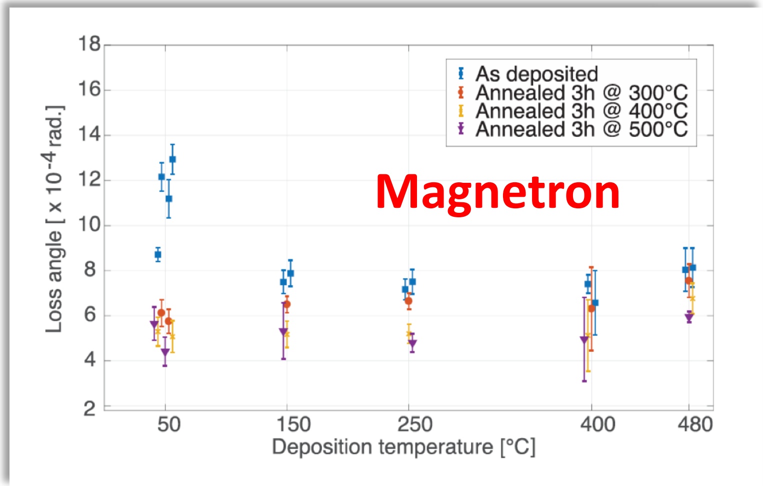
Received 10 November 2017, revised 2 February 2018
Accepted for publication 7 February 2018
Published 23 February 2018

CrossMark

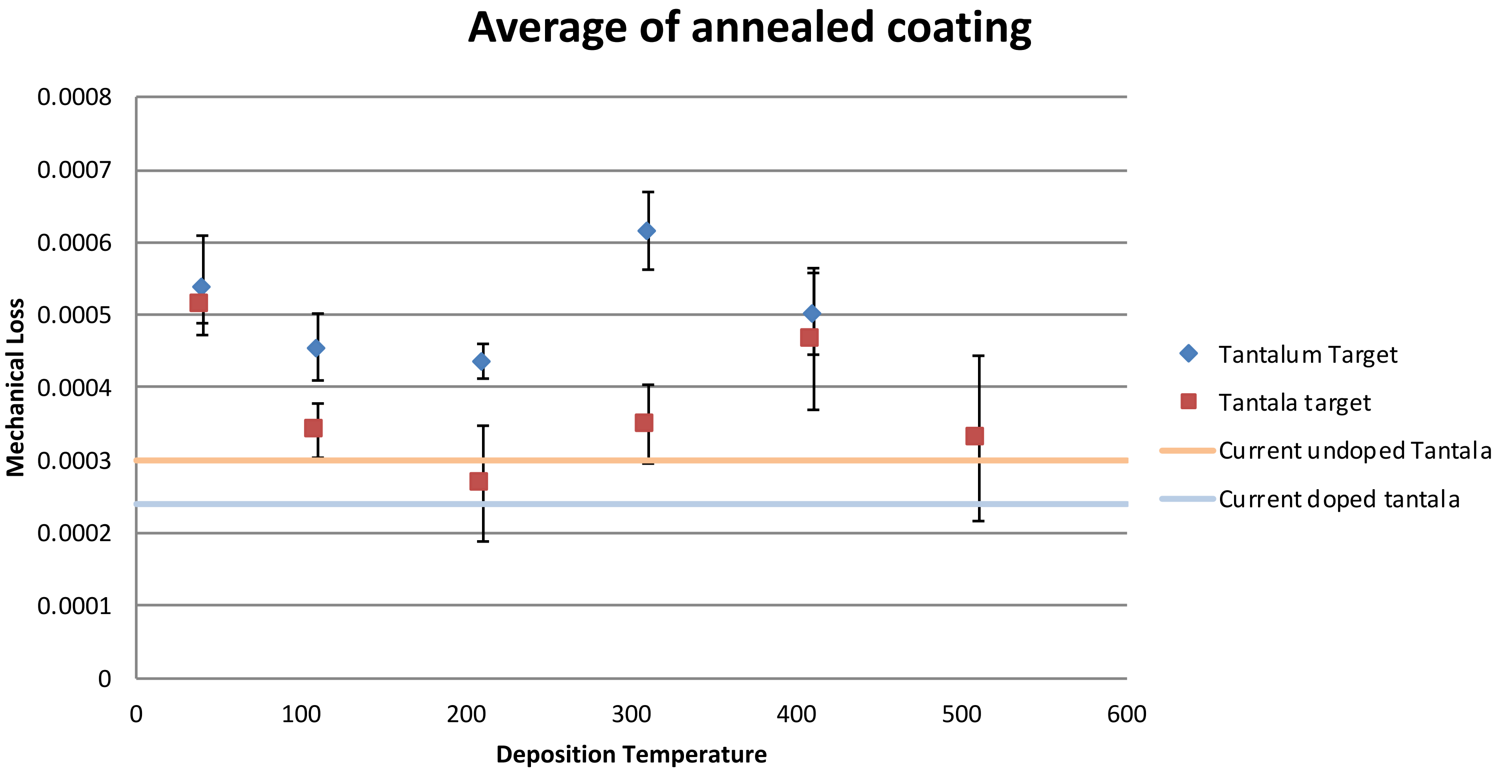
Abstract

Brownian thermal noise in dielectric multilayer coatings limits the sensitivity of current and future interferometric gravitational wave detectors. In this work





Tantala Mechanical Loss



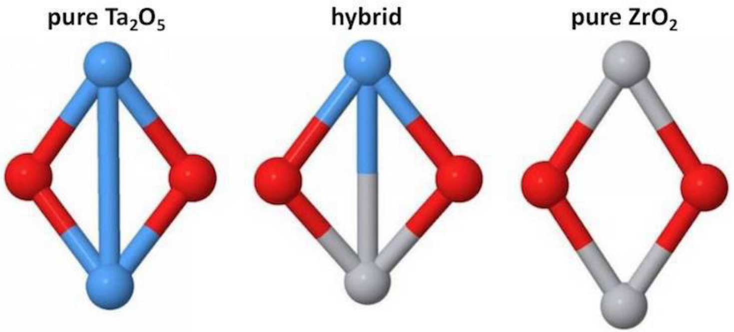
Lowest Average loss – $2.6\text{x}10^{-4}$ **undoped** tantala

Increase in loss after 200 due to deposition parameters? Stoichiometry? or real effect?

*Flaminio, Raffaele, et al. *Classical and Quantum Gravity* 27.8 (2010): 084030.

Zr:Ta_2O_5 coatings - motivation

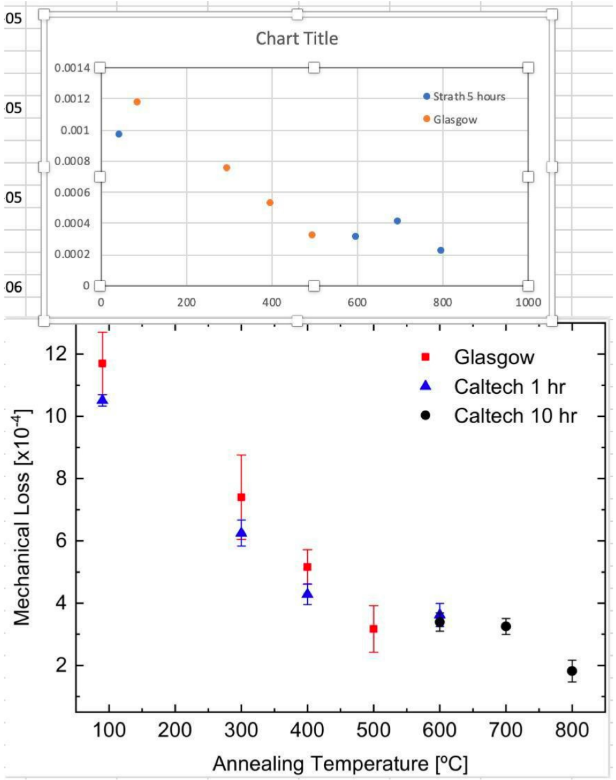
- Atomic simulation work carried out at the University of Glasgow (Glasgow group and particularly K. Evans, R. Bassiri, and K. Borisenko (Oxford)) predicted that alternative metal species, such as zirconium, could alter the dynamical behaviour of the hybrid fragments shown below and thus further reduce the mechanical dissipation.
- Marty Fejer (Stanford) and Steve Penn (HWS) also identified zirconium as a stabilising alloy which could be used to increase the crystallisation temperature, and thus provide routes to subject mirror coatings to higher heat treatment temperatures (typically higher heat treatments reduce the mechanical dissipation, however titania-tantala alloys will typically crystallise by 700C.

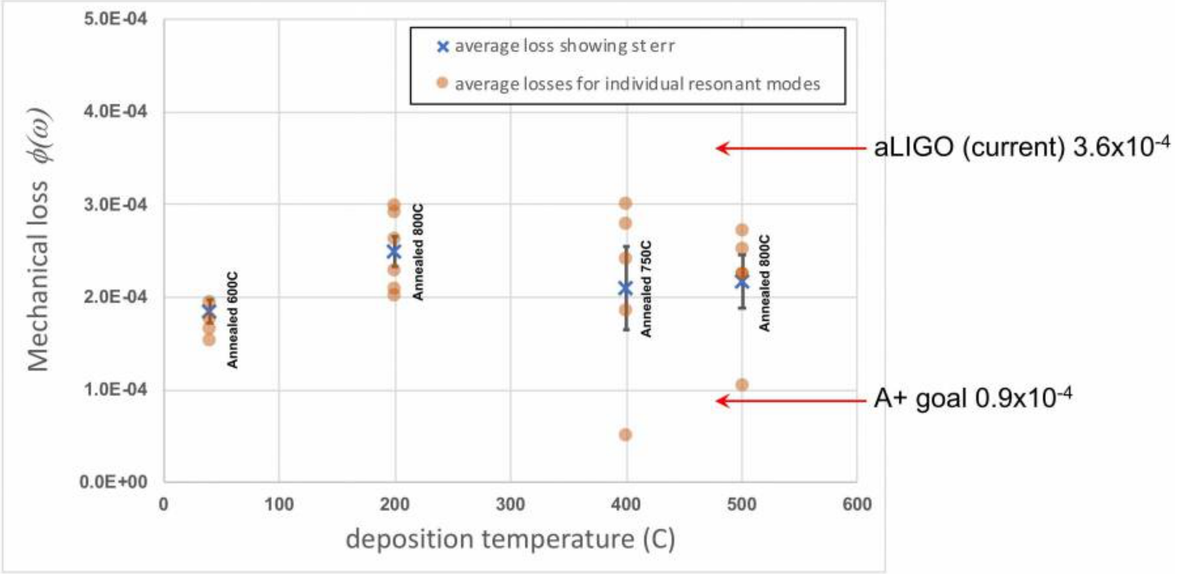


variants of the 4 atom planar fragments found in Ta_2O_5 and ZrO_2:Ta_2O_5 models.

Zr:Ta_2O_5 coatings - mechanical loss

- Coatings produced by Strathclyde group, using a new IBS technique, show losses around 2x lower than measured in Ti:Ta_2O_5 used in aLIGO
  - Following predictions of (a) structural modelling and (b) increase of crystallisation temperature, allowing higher temperature annealing to reduce loss
  - Very promising for reducing coating thermal noise for A+



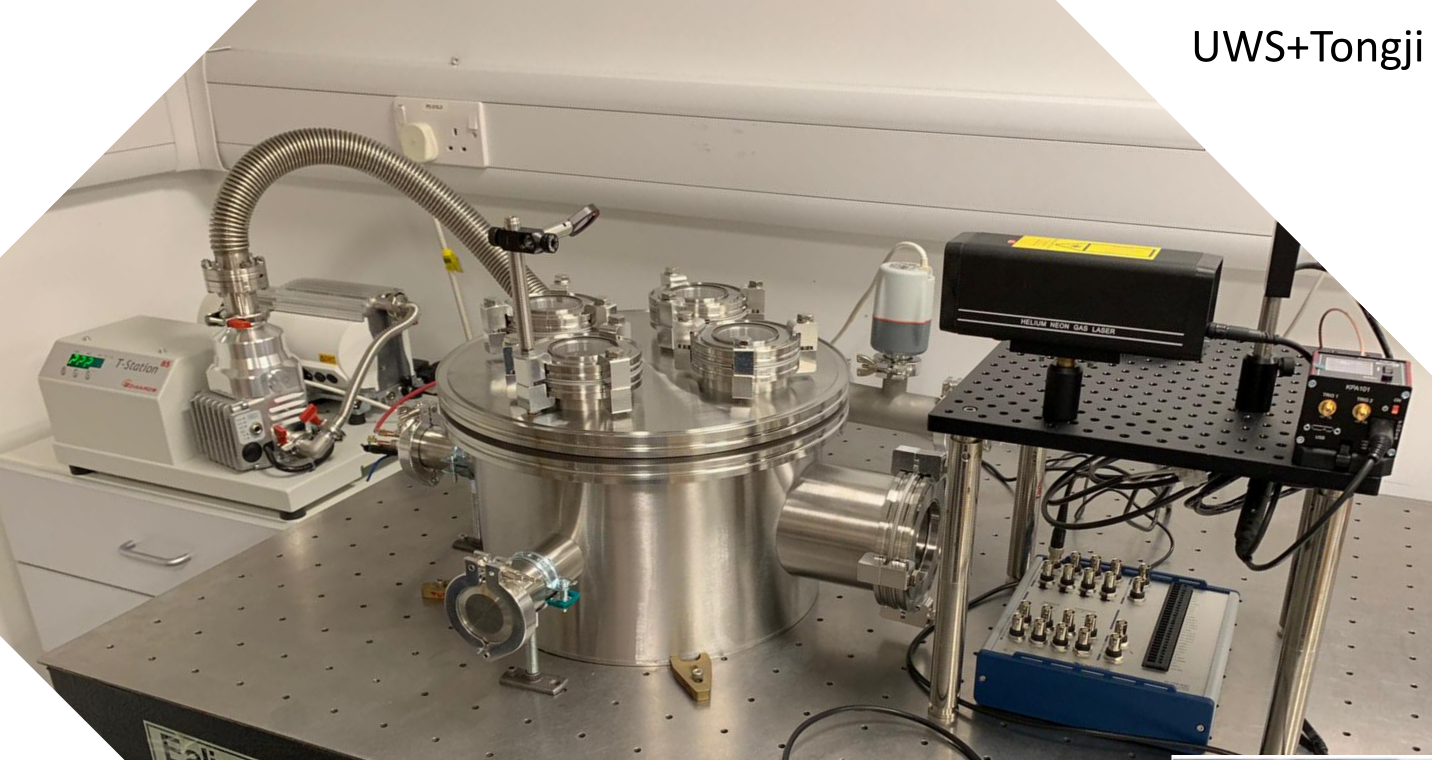


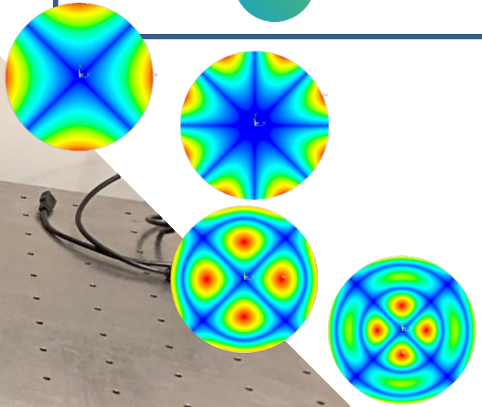
aLIGO (current) 3.6x10^{-4}

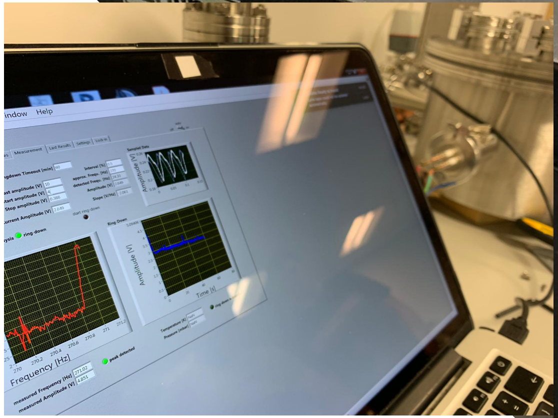
A+ goal 0.9x10^{-4}

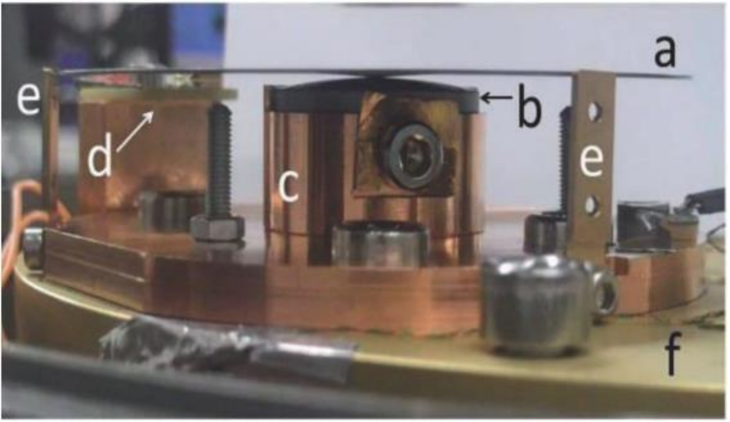
UWS+Tongji

GrEAT

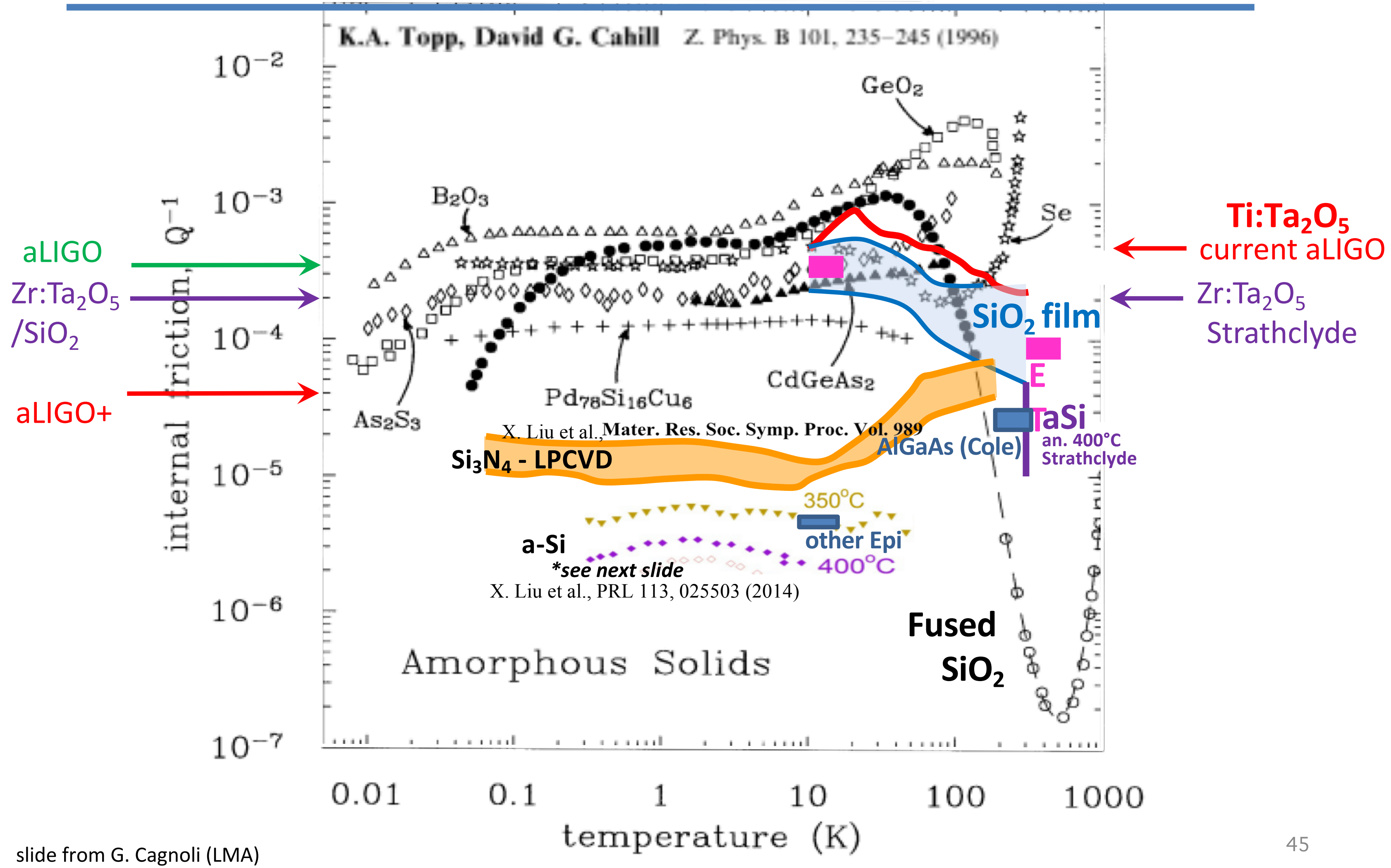








Summary



slide from G. Cagnoli (LMA)

Conclusions

- Significant effort being invested by UK groups to design, fabricate and characterise optical coatings relevant to future and 3G GW detectors.
- aSi coatings highly attractive solution – but in mixed material design + 1550 nm
- Zr:Ta_2O_5 shows repeatable loss at the level $\phi = 2.0 \times 10^{-4}$ (40% reduction c.f. Ti:Ta_2O_5).
- Direct side-by-side comparison of ECR-IBD and RF-IBD coatings in ”same” lab in 2019.
- Successful MBE growths of GaP on silicon –> development/optimisation of GaP/AlGaP.
- *We thank the LSC, Virgo, KAGRA and ET communities for support and encouragement!*

Questions?

Materials

- Ta_2O_5 – recheck ultimate ϕ on pure tantala (ECR) – new system + uniform + GeNS
- ZrO_2:Ta_2O_5 – as above
- TiO2:Ta_2O_5 – as above – Qn: how does Ti and Zr doping compare using ECR re ϕ.
- Ti++ – increase Ti content and check TiO_2:ZrO_2:Ta_2O_5 -> increase *n*, reduce thickness

- ZrO_2 – pure zirconia for comparison

- $LaTiO_3$ – should have ϕ for initial tests completed soon – repeat if interesting

- V_2O_5 – vanadia to compare ϕ vs structure (Raman), since v similar structure to tantala

- Sc_2O_3 – low absorption at 1064nm from Collorado State (Krous 2010, thesis) – check ϕ
- HfO_2 – compare ECR to RF

- aSi / SiNx – we will return to this when cryopumps are installed on systems (2019)

- Fluorides – no immediate plans, but might need to consider this later in 2019 if above materials do not look attractive enough for A+.

Low index too: SiO2 and Al2O3 – both trialed in ECR system but not optimised

Target materials for above (excl. fluorides) are in lab

Processes and further collaborative work

- Priority 1: quantify benefit of ECR vs RF regarding ϕ.
  (effect of dep rate, ion energy, *etc*)

- UWS: will use Microdyn system (microwave plasma assist DC magnetron sputtering) to:
  - Pure Sc_2O_3
  - Pure Ta_2O_5 at low, standard and high microwave assist power ("microwave annealing")
  - TiO_2:Ta_2O_5 (aim for 15% TiO_2 in Ta_2O_5)
  - ZrO_2:Ta_2O_5 (aim for 15% ZrO_2 in Ta_2O_5)

- Strath+UWS: Install plasma assist source from UWS in IBD systems in Strathclyde (oxygen = standard, but will investigate He "tickling" as alternative to elevated temperature dep)

- New grant with commercial partner (Gooch and Housego) to investigate scale-up of the ECR process.

- Production of multilayer coatings for further characterisation (+ direct TN!).