Development of ultra-low optical and mechanical loss aSi coatings using novel ECR ion beam deposition

Optical absorption of amorphous silicon coatings

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LIGO-G1601200
“Take home message”

Recent results from UWS/UG now suggest:

- It is possible to reduce optical absorption in IBS aSi coatings, whilst maintaining low $\phi$.

- Heated deposition of IBS aSi films likely to gain similar benefits in atomic structure/mechanical loss as heated e-beam deposition (as observed by Berkley group).
Background

Original requirements for aLIGO (at 1064nm):

- Absorption < 0.5 ppm required (goal < 0.3 ppm)
- Scatter < 2 ppm required (goal < 1 ppm)
- ITM transmission: \((5 \pm 0.25) \times 10^{-3}\)
- ETM transmission: < 10 ppm (goal < 5 ppm)
- Test Mass HR matching = \(\frac{2 \times (T_1-T_2)}{T_1+T_2}\) < \(1 \times 10^{-2}\) required (goal \(5 \times 10^{-3}\))
- AR reflectivity: 200 ± 20 ppm
- Mechanical loss: \(3 \times 10^{-5}\) (goal \(1 \times 10^{-4}\))

 Likely requirements for aLIGO+ and beyond?
PVD (Physical vapour deposition)

The continued challenges in PVD technology

- Uniform deposition on large area: difficult
- Multi component deposition: even more difficult

Deposition profile/conditions is somewhat fixed and limited by the geometry of the process.
Ion beam deposition (IBD)
ECR ion source at UWS
Development of ECR-IBD

ECR plasma cavity (microwave)

Divergent Ar ion beam

focus

ground
Development of ECR-IBD

Compact $\lambda/4$ microwave cavity
- filament-free
- maintenance free
- low current
- extraction potential 0-20 kV

Forward diffusion inside the magnetic field

Area of maximum power coupling

Extraction plane

~ $1/4 \sim 3$ cm at 2.45 GHz
Comparison to standard IBS

Filament and extractor grid provide high-current (possible contamination and expensive running costs) 50 to 1500eV and 75 to 700mA (for Veeco 16cm RF)
Development of ECR-IBD
Development of ECR-IBD
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);

Pump beam, 1550 nm

Probe beam, 1620 nm

Lock-in amplifier

Sample

Detector

Slides courtesy of J. Steinlechner (IGR, Glasgow)
Absorption measurements - Glasgow

Pump beam changes refractive index of an element in the probe beam

Slides courtesy of J. Steinlechner (IGR, Glasgow)
Absorption measurements - Glasgow

We measure this phase difference by imaging the plane 1 Rayleigh range from the intersection point (virtual detection plane)

$\Delta \phi \sim \Delta \frac{I}{I}$

The wavefront from this element is different from the rest of the beam

Pump beam changes refractive index of an element in the probe beam

Slides courtesy of J. Steinlechner (IGR, Glasgow)
Absorption measurements - Glasgow

Getting absorption by comparing signal to calibration substrate with known absorption

We measure this phase difference by imaging the plane 1 Rayleigh range from the intersection point (virtual detection plane)

$\Delta \phi \sim \frac{\Delta I}{I}$

The wavefront from this element is different from the rest of the beam

Pump beam changes refractive index of an element in the probe beam

Slides courtesy of J. Steinlechner (IGR, Glasgow)
aSi coatings fabricated using ECR-IBD

20mm JGS3 silica witness samples (optical characterisation and absorption)

Cross-section SEM image
aSi coatings fabricated using ECR-IBD

silica cantilevers, coated with aSi
Absorption measurements on aSi – 1550 nm

- 1550 nm
- Absorption significantly lower than for ATF coatings
- Refractive index ~3.4 from transmission measurements
- UWS measured on a ~660 nm layer
- ATF measured on a 500 nm layer
  → both scaled to HR coating

* measurement limited by substrate absorption
Absorption measurements on aSi – 1064 nm

Absorption/HR coat. [ppm]

Heat treatment temperature [°C]

- UWS
- ATF

3500 ppm
135 ppm
Mechanical loss

Initial mechanical loss measurements on silica cantilevers
Berkeley high temperature deposition

- As discussed by M. Fejer yesterday (see G1601192-v1)
- Heated deposition reduces mechanical loss much further than post-heat treatment alone.
  \[ \sim 10^{-4} \text{ vs } \sim 10^{-6} \]
- 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?

High-temperature deposition

- Ceramic heater
- Copper substrate holder
- Si target
- Source
Random spread in absorption – no clear benefit in heated deposition in initial tests

Strong evidence that room temperature coatings have been contaminated – strangely reducing the absorption further – however index also lower than expected
High-temperature deposition – mechanical loss

Mechanical Loss of aSi

So what happens???
High-temperature deposition – mechanical loss

Difficult (but good!) problem:

uncoated cantilever – annealed twice at 400C

\[ \phi_{\text{uncoated}} = 1.64 \times 10^{-6} \]

coated cantilever – annealed at 400C

\[ \phi_{\text{coated}} = 1.86 \times 10^{-6} \]

\[ y = 4.29963 \times 10^0 e^{-7.98922 \times 10^{-4} x} \]
\[ R^2 = 9.99234 \times 10^{-1} \]

\[ y = 2.87802 \times 10^0 e^{-0.06375 \times 10^{-4} x} \]
\[ R^2 = 9.99249 \times 10^{-1} \]
High-temperature deposition – mechanical loss

**Mechanical Loss of aSi**

- **Tantala Mechanical loss** (aLIGO)
- **As Deposited aSi**
- **aSi Mechanical loss 200°C deposition**
- **As Deposited annealed at 400°C for 1 hour**

**Graph Details:**
- **Y-axis:** Mechanical Loss $\phi(\omega)$
- **X-axis:** Frequency (KHz)
- **Data Points:**
  - Orange triangle: Tantala Mechanical loss (aLIGO)
  - Green square: As Deposited aSi
  - Blue diamond: aSi Mechanical loss 200°C deposition
  - Purple circle: As Deposited annealed at 400°C for 1 hour

**Legend:**
- Orange triangle: Tantala Mechanical loss (aLIGO)
- Green square: As Deposited aSi
- Blue diamond: aSi Mechanical loss 200°C deposition
- Purple circle: As Deposited annealed at 400°C for 1 hour
High-temperature deposition – mechanical loss

Annealing the 200°C aSi coating at 400°C, measurement approaching experimental uncertainty, at the level of $1 \times 10^{-5}$.

Likely factor 25 reduction in loss achievable
High-temperature deposition – mechanical loss

Results are on the way!
Characterisation – bandgap associated absorption

Tauc plot – UWS aSi

\((\alpha h\nu)^{0.5}\)

\(h\nu\)
Characterisation – bandgap associated absorption

Average bandgap energy 1.4eV (commonly reported 1.1-1.5eV for a-Si)
Characterisation – Raman

See poster by Zeno Tornasi (Glasgow)
Thermal noise

- We can use a multi material design
- Some bilayers of SiO$_2$ and Ta$_2$O$_5$ are used to reduce the laser power
- In lower layers amorphous silicon can be used to improve thermal noise due to a high refractive index and low loss
What does this mean for thermal noise?
… if we want less than 1ppm absorption from the aSi:

At 1064 nm RT:

- We need 8 bilayers of SiO$_2$ and Ta$_2$O$_5$ to reduce the laser power
- For an ITM with T = 1.4% we can’t improve the coating using aSi in lower layers
- For an ETM with T = 6 ppm we need 4 bilayers of SiO$_2$ and aSi

- Thermal noise improvement* compared to a pure SiO$_2$ and Ta$_2$O$_5$ coating:

  Room temperature:
  ITM: - 0%
  ETM: - 28%
  total: -18% 21.5%

Almost no improvement by reducing mechanical loss further (limited by silica loss and ITM thermal noise)

*Loss for aSi: 1.2e-4 measured on UWS aSi coatings at room temperature
What does this mean for thermal noise?

... if we want less than 1ppm absorption from the aSi:

At 1550nm RT:

- We need 5 bilayers of SiO$_2$ and Ta$_2$O$_5$ to reduce the laser power
- For an ITM with T = 6000 ppm we need 2 bilayers of SiO$_2$ and aSi
- For an ETM with T = 6 ppm we need 5 bilayers of SiO$_2$ and aSi
- Thermal noise improvement* compared to a pure SiO$_2$ and Ta$_2$O$_5$ coating:

  120 K  
  ITM: -21%  
  ETM: -38%  
  total: -32%

  20 K  
  -20%  
  -36%  
  -31%

*Loss for aSi: values from commercial coatings; no cryogenic measurements on UWS coatings
Conclusion from UWS + GU investigations using ECR-IBD

aSi attractive high-index material choice for aLIGO+ and beyond

- Optical absorption of 20ppm for HR stack feasible (reason due to unique dep parameters – low dep rate + high ion energy)
- Mechanical loss $\sim 5 \times 10^{-5}$ (room temp deposition + heat treatment at 400C)

Heated deposition

- First evidence that heated substrates + ion-beam deposition can reduce mechanical loss below that achievable through same temperature post-deposition annealing
- Mechanical loss $\sim 1 \times 10^{-5}$ for aSi deposited at 200C then heat treated to 400C

Future work

- Complete studies on aSi deposited at elevated temperatures
- Investigate effect of elevated temperature on $\text{Ta}_2\text{O}_5$
- Investigate effect of shifting bandgap absorption edge in aSi through doping (H, Al, N etc) – with particular relevance to 1064nm use.
Towards a more ordered future...
Plan to develop AlGaP interference coatings on silicon

Key milestones:

- March 2016: all equipment delivered (P cracker, P recovery system, auxiliary equip.)
- June 2016: installation of P cracker and recovery system
- August 2016: test growths of AlGaP begin
Conclusion from UWS + GU investigations using ECR-IBD

aSi attractive high-index material choice for aLIGO+ and beyond

- Optical absorption of 20ppm for HR stack feasible (reason due to unique dep parameters – low dep rate + high ion energy)
- Mechanical loss < 1x10^{-4} (room temp deposition + heat treatment at 400C)

Heated deposition

- First evidence that heated substrates + ion-beam deposition can reduce mechanical loss below that achievable through same temperature post-deposition annealing
- Mechanical loss ~1x10^{-5} for aSi deposited at 200C then heat treated to 400C

Future work

- Complete studies on aSi deposited at elevated temperatures
- Investigate effect of elevated temperature on Ta_{2}O_{5}
- Investigate effect of shifting bandgap absorption edge in aSi through doping (H, Al, N etc) – with particular relevance to 1064nm use.
- Further low temperature absorption and thermal noise evaluation.