

# Crystalline silicon fibres in cryogenic suspension systems for next-generation gravitational wave detectors

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**Abstract.** With the plans for the Einstein Telescope to operate at cryogenic temperatures, there is a need for low-noise crystalline suspension systems to reach the required sensitivity goals. Crystalline silicon is a promising candidate for suspension elements due to its favourable properties at cryogenic temperatures, including a high-quality factor, thermoelastic nulling regions, and thermal conductivity. It has been shown that these properties, as well as mechanical strength, are dependent on the surface quality and fabrication process of the material. An optimized production process for crystalline fibers is therefore crucial, along with thorough characterization of their properties. In this study, we present the characterisation of crystalline silicon fibres grown using the float-zone technique by the Institut für Kristallzüchtung (IKZ) Berlin. These initial results demonstrate the potential feasibility of producing high-quality silicon fibres and indicate that, with further optimisation and characterisation, silicon fibres have the potential to achieve the necessary low thermal noise performance, reinforcing silicon's suitability as a candidate material for next-generation gravitational wave detectors.

## 1 Fibres in a cryogenic suspension system

The next generation of gravitational wave detectors, such as the proposed Einstein Telescope (ET) and Cosmic Explorer, will require advanced low-noise mirror suspensions to suppress thermal and seismic noise and reach their sensitivity goals [1] [2]. The currently used material, fused silica, is not a viable candidate for cryogenic suspension systems that are essential for the ET Low Frequency (ET-LF) detector, as it generates excessive thermal noise at low temperatures dominated by a high mechanical loss [3]. To overcome this limitation, a shift to crystalline materials is under consideration.

Crystalline silicon is a promising candidate for suspension elements due to its favourable properties at cryogenic temperatures; high-quality factor [4], high thermal conductivity [5], and thermoelastic nulling at 18K and 123K [6]. Those properties, as well as mechanical strength, are dependent on the surface quality and fabrication process of the material. Crystalline materials, such as sapphire and silicon, offer superior mechanical and thermal performance at low temperatures; however, their properties must be thoroughly characterised to assess their suitability for monolithic suspensions in next-generation detectors. This work reports on the fabrication and detailed characterisation of monocrystalline silicon fibres, establishing their potential as suspension elements for next-generation gravitational wave detectors.



## 2 Fibre production and characterisation

The silicon fibres under investigation have been developed by Leibniz-Institut für Kristall-züchtung (IKZ) and were fabricated using the float-zone (FZ) technique; a well-established method for producing ultra-high purity monocrystalline silicon [7]. The setup for the production process is shown in Fig. 1 (left). IKZ has demonstrated a stable and repeatable process for producing monocrystalline silicon fibres across a range of lengths and diameters. This method addresses the poor surface quality observed in previous fabrication techniques [8]. As shown in Fig. 1 (right), the samples possess a smooth and uniform surface finish. A detailed and complete characterisation of the material elements is essential before a choice for suspension material for the ET payload can be made.

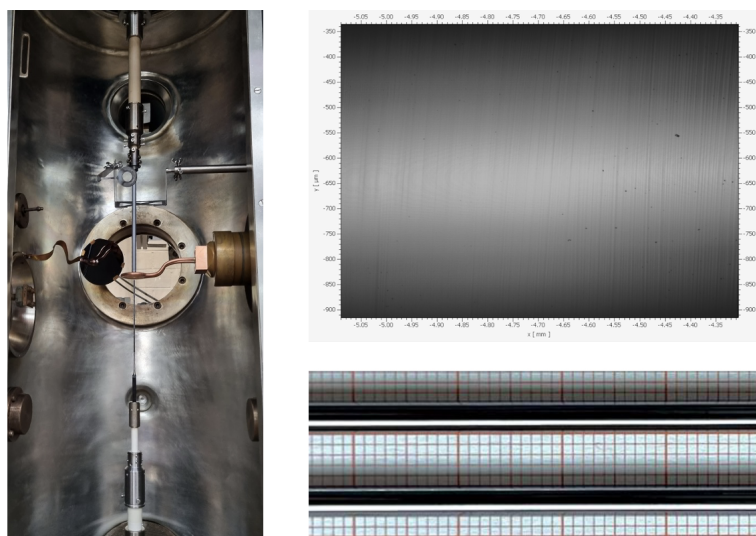


Figure 1: Left: Image of the furnace post-production, once it has been brought back to room temperature. A grown fibre can be observed situated below the copper coil. Right: Surface quality of the fibre at 50x magnification (top) obtained with a surface profiler, and close-up image of the surface quality of two fibres (bottom).

### 2.1 Surface quality, crystallinity and mechanical loss

While thermoelastic dissipation dominates mechanical loss at room temperature, surface and bulk effects become limiting factors at cryogenic temperatures [9]. Achieving atomically smooth surfaces is therefore critical as rough finishes, such as found with mechanically ground silicon, lead to high mechanical loss values and significantly reduced fracture strength [8] [10].

The surface quality and crystallinity of the fibres produced by IKZ have been tested. The crystal orientation was analysed using X-ray diffraction; all fibres were monocrystalline and the crystal orientation was preserved along the fibre. The surface quality was evaluated using an optical surface profiler and scanning electron microscopy. The fibres exhibited an RMS surface roughness of  $0.15\ \mu\text{m}$ , and both measurements indicated diameter variations of less than  $<1\%$  along the fibre length. No visible microcracks or indentations were observed on the surface. These results suggest that the contribution of surface defects to the mechanical loss of the fibres is expected to be minimal.

### 2.2 Thermal conductivity

At lower temperatures, around 18K, radiation becomes ineffective and heat must be removed almost entirely through thermal conduction along the suspension elements [11]. A high thermal conductivity is therefore essential for the payload components used in cryogenic systems. Silicon exhibits significantly higher thermal conductivity than fused silica, with a pronounced peak around 26K [5]. The thermal conductivity of a 3 mm uniform-diameter control sample produced by IKZ has been measured, and the results are consistent with the recommended Touloukian curve for a high-purity material [5]. This proves that the growth process preserves the high thermal conductivity of silicon.

### 2.3 Tensile strength measurements

The mechanical strength of the silicon fibres was evaluated to ensure that such fibres could support the 211 kg test mass of the ET-LF design; this was measured using along-axis linear drive tensile tests and four-point bending techniques.

Tensile tests were performed using self-tightening clamps and a worm drive to apply a controlled tension [8]. The applied force was recorded by a load cell, and fracture events were captured with a high-speed camera to determine the breaking stress. Four-point bending tests are commonly used in the gravitational-wave community to assess the bond strength of hydroxide catalysis joints [12]. The sample was supported on two lower rods while a load was applied from above to generate a constant bending moment. The tensile stress was evaluated, with preliminary results showing a higher median strength than achieved during traction measurements [8].

The measured breaking strengths ranged from approximately 120 to 460 MPa, with a median value from the four-point bending test around three times that obtained from along-axis traction tests. This suggests that alignment issues in the traction setup may have reduced the measured strength. These issues are likely mitigated in the four-point bending configuration, as better alignment strongly influences the breaking point along the fibre. Preliminary studies suggest that improved alignment increases the measured strength of silicon fibres.

## 3 Summary

Crystalline silicon fibres produced via the float-zone technique by IKZ Berlin have been characterised for their suitability in cryogenic suspension systems for next-generation gravitational wave detectors. The fibres exhibit high crystallinity, uniform diameter, and smooth surfaces, supporting low mechanical loss and high tensile strength predictions. Thermal conductivity measurements confirm efficient heat extraction at the proposed operating temperatures of 18K. These results indicate that float-zone silicon fibres could meet the essential thermo-mechanical requirements for low-noise cryogenic suspensions, reinforcing silicon's potential as a material for future detector suspension elements.

## References

- [1] Abac A et al. "The Science of the Einstein Telescope". In: (Mar. 2025). arXiv: 2503.12263 [gr-qc].
- [2] Reitze D et al. "Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO". In: *Bull. Am. Astron. Soc.* 51.7 (2019), p. 035. arXiv: 1907.04833 [astro-ph.IM].
- [3] Robinson J M et al. "Thermal noise and mechanical loss of SiO<sub>2</sub>/Ta<sub>2</sub>O<sub>5</sub> optical coatings at cryogenic temperatures". In: *Opt. Lett.* 46.3 (2021). DOI: 10.1364/OL.413758.
- [4] Nawrodt R et al. "High mechanical Q-factor measurements on silicon bulk samples". In: *Journal of Physics: Conference Series* 122 (July 2008), p. 012008. DOI: 10.1088/1742-6596/122/1/012008.
- [5] Touloukian Y S et al. "Thermophysical properties of matter - the TPRC data series. Volume 1. Thermal conductivity - metallic elements and alloys. (Reannouncement). Data book". In: 1970.
- [6] Nawrodt R et al. "Investigation of mechanical losses of thin silicon flexures at low temperatures". In: *Classical and Quantum Gravity* 30.11 (May 2013), p. 115008. ISSN: 1361-6382. DOI: 10.1088/0264-9381/30/11/115008.
- [7] Rudolph P and Kakimoto K. "Crystal Growth from the Melt under External Force Fields". In: *MRS Bulletin* 34 (Apr. 2009), pp. 251–258. DOI: 10.1557/mrs2009.75.
- [8] Cumming A V et al. "Silicon mirror suspensions for gravitational wave detectors". In: *Classical and Quantum Gravity* 31.2 (2013), p. 025017.
- [9] Reid S et al. "Mechanical dissipation in silicon flexures". In: *Physics Letters A* 351.4 (2006), pp. 205–211. ISSN: 0375-9601. DOI: <https://doi.org/10.1016/j.physleta.2005.10.103>.
- [10] Eddolls G. "Design, build and characterisation of a prototype single crystalline silicon cryogenic suspension for 3rd generation gravitational wave detectors". PhD thesis. University of Glasgow, 2022.
- [11] Tomaru T et al. "Maximum heat transfer along a sapphire suspension fiber for a cryogenic interferometric gravitational wave detector". In: *Physics Letters A* 301.3 (2002), pp. 215–219. ISSN: 0375-9601. DOI: [https://doi.org/10.1016/S0375-9601\(02\)00985-4](https://doi.org/10.1016/S0375-9601(02)00985-4).
- [12] Van Veggel A and Killow C J. "Hydroxide catalysis bonding for astronomical instruments". In: *Advanced Optical Technologies* 3.3 (2014), pp. 293–307. DOI: doi:10.1515/aot-2014-0022.