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# 超高精度 X 射线光学元件加工技术

## 摘要

高精度 X 射线单晶硅反射镜是同步辐射光源和自由电子激光装置中的关键光学元件，其面形精度、斜率误差和表面粗糙度直接影响衍射极限聚焦、光束亮度和空间分辨率等核心性能。长期以来，高品质 X 射线单晶硅反射镜主要依赖国外供应，发展自主可控的超高精度 X 射线光学元件加工技术具有重要意义。然而，受单晶硅材料难加工特性、复杂曲面误差确定性控制难度以及近零缺陷表面创成能力不足等因素制约，国内元件在纳米级面形、纳弧度斜率和原子级超光滑表面等全空间频段指标方面仍存在差距。

针对上述问题，本文提出了“超精密磨削成形—气囊快速抛光—磁流变精密修形”组合加工工艺路线，突破了单晶硅 X 射线光学元件亚纳米级低损伤表面加工关键技术。通过研究单晶硅材料表面力学特征，揭示了磁场、流量、浸入深度等工艺参数对磁流变抛光力的影响规律，建立了基于磨料优化配比的低应力磁流变抛光方法，实现了单晶硅元件低损伤表面创成。同时，建立了宽范围磁流变去除函数调控方法，发展了不同空间尺度去除函数与元件频谱误差相匹配的确定性修正算法，可根据表面误差分布特征选择兼顾修形精度与加工效率的去除函数组合，实现元件全空间频段纳米级误差修正。

基于上述技术，完成了 600 mm 单晶硅反射镜和 X 射线柱面 KB 镜研制。其中，600 mm 单晶硅反射镜面形误差 PV 值达到 7.1 nm，表面粗糙度 RMS 达到 0.18 nm；柱面 KB 镜面形误差 PV 值达到 6.38 nm，表面粗糙度 RMS 达到 0.23 nm。经 X 射线显微成像应用验证，所研制元件成像效果达到 J-Tec 同类元件水平。该研究为同步辐射光源和自由电子激光装置中高性能 X 射线光学元件的自主研制奠定了技术基础。

## 关键词

同步辐射光源；自由电子激光；X 射线光学；单晶硅反射镜；超精密加工

## Abstract

Single-crystal silicon mirrors are enabling optical components in synchrotron radiation sources and X-ray free-electron laser facilities, where residual figure error, slope error, and surface microroughness directly limit diffraction-limited focusing, brilliance preservation, and imaging resolution. The fabrication of high-quality X-ray mirrors remains technically demanding because single-crystal silicon is brittle and damage-sensitive, while X-ray optics require deterministic control of surface errors over a broad spatial-frequency range together with near defect-free, atomically smooth surfaces.

Here, we report an integrated fabrication process combining ultra-precision grinding, rapid bonnet polishing, and magnetorheological finishing for high-precision X-ray optical components. The surface mechanical response of single-crystal silicon was investigated, and the influence of magnetic field strength, slurry flow rate, and immersion depth on the magnetorheological finishing force was clarified. Based on optimized abrasive formulations, a low-stress magnetorheological finishing strategy was developed to suppress surface and subsurface damage during material removal.

To enable deterministic correction over multiple spatial scales, a tunable removal-function control method was established, and a frequency-domain matching algorithm was developed to correlate removal functions with measured surface-error spectra. This approach allows suitable removal-function combinations to be selected according to the spatial distribution of surface errors, thereby improving both correction accuracy and processing efficiency. As a result, nanometer-level error correction across the relevant spatial-frequency range was achieved.

Using the developed process, a 600 mm single-crystal silicon mirror and a cylindrical Kirkpatrick–Baez mirror were fabricated. The 600 mm mirror achieved a peak-to-valley figure error of 7.1 nm and a root-mean-square surface roughness of 0.18 nm, while the cylindrical KB mirror achieved a peak-to-valley figure error of 6.38 nm and a root-mean-square roughness of 0.23 nm. X-ray microscopic imaging tests further confirmed that the fabricated optics delivered imaging performance comparable to that of similar J-Tec components. These results demonstrate a viable process route for the domestic fabrication of high-performance X-ray optics for synchrotron radiation and X-ray free-electron laser applications.

## Keywords

Synchrotron radiation sources; X-ray free-electron lasers; X-ray optics; single-crystal silicon mirrors; ultra-precision fabrication

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