

PHOTOCATHODE PREPARATION STUDIES BASED ON A PHOTOCATHODE IN-SITU RESEARCH APPARATUS*

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Abstract

The photocathode in-situ research apparatus integrates preparation, characterization, and environmental control under ultra-high vacuum to prevent surface contamination, establishing a real-time “preparation-monitoring-regulation” closed-loop for high-performance photocathodes such as Cs₂Te. Following comprehensive commissioning, which is utilized for Cs₂Te photocathode preparation, CsBr protective layer deposition, and temperature-dependent performance measurements. In-situ grazing-incidence wide-angle X-ray scattering (GIWAXS) characterization at the Shanghai Synchrotron Radiation Facility (SSRF) revealed that the crystal structure of sequentially deposited Cs₂Te photocathode changes synchronously with the quantum efficiency (QE) improvement, validating the apparatus for studying high QE photocathodes.

INTRODUCTION

We have prepared high QE Cs₂Te photocathodes with internationally leading performance that have been successfully applied in the SHINE (Shanghai High repetition rate XFEL and Extreme light facility) commissioning [1], demonstrating excellent long-term stability. An innovative intermittent Te and continuous Cs deposition eliminates QE fluctuations caused by equipment and operator variations [2]. A dedicated in-situ research apparatus was designed, assembled, and commissioned to systematically study the intrinsic mechanisms behind the high QE and long lifetime of Cs₂Te, guiding further optimization.

This paper consists of three sections: the first introduces the photocathode in-situ research apparatus, the second details the Cs₂Te photocathode preparation based on the apparatus, and the third describes the GIXWAS characterization applied during the preparation process.

I. APPARATUS AND ITS FUNCTIONS

The photocathode in-situ research apparatus integrates four functions: preparation, testing (characterization), environmental control, and data integration, with detailed as follows:

- Preparation: Photocathode deposition equipment, such as PVD.
- Testing: QE measurement and in-situ characterization (e.g., GIWAXS).

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- Environmental Control: UHV (10⁻⁸ Pa) environment with temperature control (-100 °C to 450 °C).
- Data Integration: Software control of all subsystems, real-time collection and analysis of preparation parameters and performance data.

The photocathode in-situ research apparatus based on synchrotron radiation beamlines integrates material synthesis and real-time characterization, utilizing high-brightness synchrotron X-rays (5–150 keV) to enable in-situ preparation, characterization, and performance testing of photocathodes under controlled conditions (Fig. 1). It mainly consists of the following components:

- Vacuum Chamber: A spherical SS 316L UHV chamber, equipped with ion pumps, NEG pumps, and vacuum gauges, ensures high-performance photocathode preparation and minimizes degradation during testing.
- Evaporation Source Unit: Evaporation sources (SAES alkali metal dispensers and slitted 304 SS capillaries containing Sb, Te, CsBr, etc.) with high-precision DC power supplies for controlled deposition. A film thickness meter (FTM) with temperature-controlled chiller to measure the deposition thickness and rate on the substrate.
- Performance Testing Module: A temperature control module for substrate heating/cooling, a drive light system with real-time optical power measurement (incident and reflected), and a photocurrent collection system (cathode-chamber/anode-mask) for photocathode QE and stability evaluation.
- Synchrotron Radiation Coupling Interface: Beryllium windows (CF63 for X-ray entrance, CF35 for fluorescence exit, and a square window for reflected/diffracted signals) maintain UHV while enabling real-time monitoring of photocathode crystallinity (via GIWAXS) and elemental composition (via XRF).

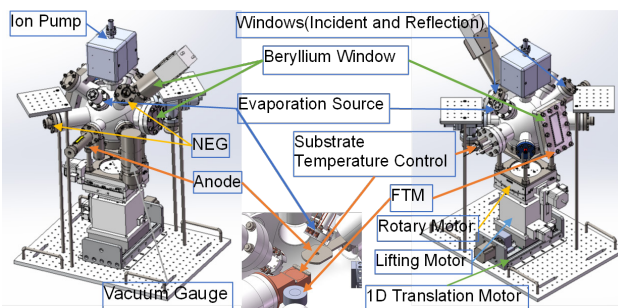


Figure 1: Schematic of the photocathode in-situ research apparatus.

II. CS₂TE PHOTOCATHODE PREPARATION

Cs₂Te photocathode preparation process within photocathode in-situ research apparatus as follows:

1. Substrate Preparation: The substrate used for Cs₂Te photocathode preparation is commercial Mo mirror (25 mm diameter, surface roughness < 5 nm), which is ultrasonically cleaned with acetone and ethanol, dried with N₂, and immediately loaded into the chamber, and the evaporation sources are replaced simultaneously.

2. Vacuum Acquisition and Evaporation Source Degassing: The chamber, substrate, and ion pump are baked at 150 °C for 72 hours for outgassing after the chamber is pumped down and leak-checked; During the bake-out, the ion pump and vacuum gauge are degassed, and evaporation sources are heated to 4 A for 30 minutes to degas. Near the end of the bake-out, the substrate is cleaned by heating at 350 °C for 6 hours, the NEG pump is degassed at 7 V for 30 minutes and then activated at 16 V for 60 minutes. The baking process is terminated, and the ion pump and vacuum gauges are turned on.

3. Substrate Cleaning and Evaporation Source Degassing: Under UHV (10⁻⁸ Pa) conditions, the substrate is again heated to 350 °C for 6 hours cleaning to achieve an atomically clean surface, followed by a repeated degassing of the evaporation sources (Cs, Te, CsBr) at 4 A for 30 minutes.

4. Light Path and Photocurrent Circuit: The optical path and photocurrent collection circuit are established.

5. Preparation and Testing: Deposition of the Cs₂Te photocathode and the CsBr protective layer. The performance testing of the Cs₂Te+CsBr photocathode is also measured.

5.1 Cs₂Te Photocathode Deposition

Under ultra-high vacuum conditions (better than 1×10⁻⁸ Pa) and with 5 mm cathode-anode gap, 200 V voltage, and 300 μW optical power, the Mo heated to 100 °C to prepared Cs₂Te photocathode by intermittent Te and continuous Cs deposition: Te is deposited intermittently to form a uniform film or islands, while Cs is continuously supplied to react with Te and form Cs₂Te, with Te deposition cycles and Cs deposition rate dynamically adjusted by real-time monitoring of temperature, vacuum pressure, film thickness, and QE to promote stoichiometric reaction. Through periodic Te replenishment and continuous Cs coverage, Te islands gradually evolve to a continuous, Cs-rich, low-defect Cs₂Te photocathode, which effectively avoids contamination and phase impurities from excessive elemental deposition, thus achieving high and stable QE, the QE of the Cs₂Te photocathode gradually rises and exceeds 10% under 280 nm UV irradiation during preparation, as illustrated in Fig. 2.

5.2 Deposition of CsBr Protective Layer on Cs₂Te Photocathode

CsBr protective layer is deposited on Cs₂Te photocathode by resistive heating to 75 °C and sublimating CsBr from a slitted SS304 tube. The CsBr particles through physical adsorption, surface diffusion, nucleation, and

grain growth, forming the continuous, uniform, and pinhole-free approximately 1-2 nm CsBr film. Which isolates residual gases (O₂, CO₂) to extend the photocathode lifetime. Under 280 nm UV LED illumination, the QE drops rapidly from about 100% to 47.5% during CsBr deposition and recovers slightly to around 55% after deposition ceases, decreases again below 45% during re-deposition, and gradually rises to about 50% after deposition ceases as shown in Fig. 3. through real-time monitoring using a FTM to yield the protective layer that balances protective with optical transparency.

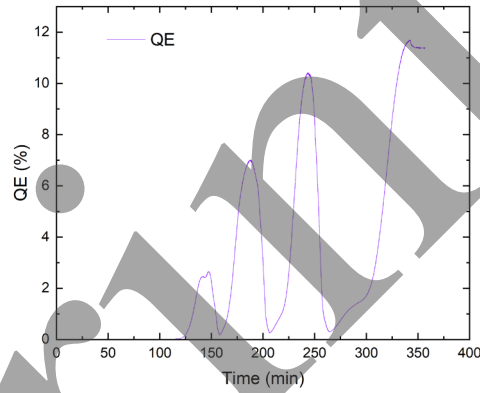


Figure 2: QE evolution of Cs₂Te photocathode during the preparation process.

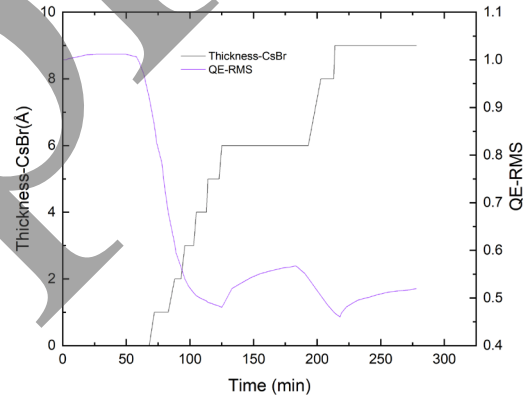


Figure 3: QE evolution of Cs₂Te+CsBr photocathode during CsBr deposition.

5.3 QE of Cs₂Te Photocathode with CsBr Protective Layer at Different Temperatures

The temperature-dependent QE of Cs₂Te+CsBr photocathode is shown in Fig. 4:

Low-Temperature (<150 °C): At relatively low temperatures, QE gradually recovers and stabilizes at a higher steady-state value. In contrast, at relatively high temperatures, QE initially drops briefly before recovery, ultimately reaching a lower steady-state QE compared to lower temperatures. showing the photocathode demonstrates stronger self-recovery capability at lower temperatures.

Medium-Temperature (150 °C - 350 °C): The photocathode QE decreases continuously and stabilizes at lower final stable-state QE. The higher the temperature, the lower the stable QE; Cs₂Te+CsBr photocathode is attributed to structural degradation, primarily involving surface

composition segregation and crystal defect accumulation, which significantly deteriorates photoemission performance.

High-Temperature (>350 °C): The QE of Cs₂Te+CsBr photocathode rapidly drops to background levels due to high-temperature-induced Cs₂Te bond breaking and Cs atom desorption, which disrupts the stability of photocathode's band structure.

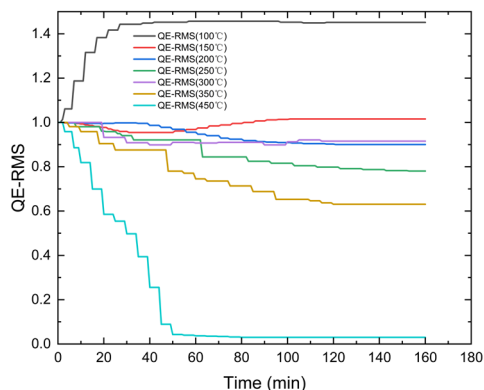


Figure 4: QE variation of Cs₂Te+CsBr photocathode at different temperatures.

III. IMPLEMENTATION OF THE IN-SITU PHOTOCATHODE PREPARATION FUNCTION

Following chamber venting, the X-ray entrance and exit blind flange were replaced with beryllium, and the substrate was changed from polished Mo to Si (100). Ultra-high vacuum (UHV) was subsequently achieved by leak detection and degassing baking, followed evaporation sources were degassed and the substrate was thermally cleaned at 450 °C for 6 hours. The photocathode in-situ research apparatus was then transferred to SSRF BL16B1 beamline for commissioning, which arrangement is illustrated in Fig. 5. All instrument operation and data collection were realized through Ethernet networking, allowing remote control of motors, evaporation source power, film thickness monitoring, temperature, and corresponding data acquisition through the radiation shielding wall.

Cs₂Te photocathode preparation based on photocathode in-situ research apparatus involved the initial deposition of 30 nm Te, followed by Cs deposition. While the QE initially increased slowly with negligible diffraction changes, reaching a critical Cs thickness triggered formation of the Cs₂Te phase characterized by abrupt QE enhancement and emergence of specific diffraction peaks. Figure 6 illustrates the corresponding QE and GIWAXS variation during preparation and annealing processes.

In-situ synchrotron-based GIWAXS enables real-time dynamic monitoring of crystal structural evolution during Cs₂Te photocathode preparation, allowing precise control of substrate temperature, Cs/Te evaporation rates and other preparation conditions. Synchrotron X-rays continuously impinge on the substrate at a grazing incidence angle below 0.2 °, enhance surface signal response and suppress substrate interference to continuously record the diffraction

patterns of nm-thick Cs₂Te films. This method effectively characterizes dynamic variations in grain size, interface defects, lattice strain and crystal texture, enabling optimization of preparation parameters for high-crystallinity, high-QE photocathodes. Real-time scattering signals show that the structural evolution: initially broad diffuse peaks characteristic of amorphous or microcrystalline states, followed by the gradual emergence of crystalline phase diffraction peaks with increasing intensity and decreasing Full Width at Half Maximum (FWHM), indicating grain expansion and improved crystallinity.

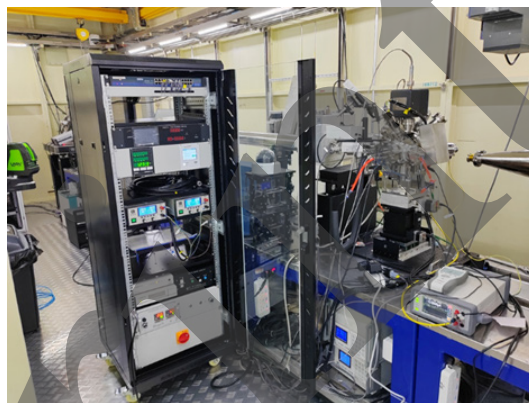


Figure 5: Layout of the photocathode in-situ research apparatus on the optical platform of SSRF beamline.

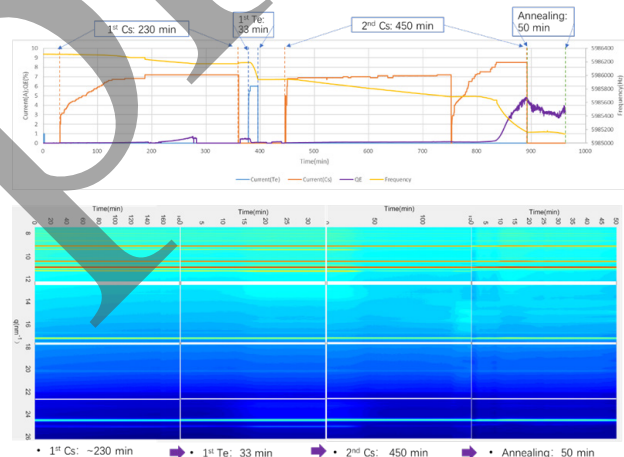


Figure 6: Variation of QE and GIWAXS signals with time during Cs₂Te photocathode preparation and thermal annealing.

CONCLUSION

The photocathode in-situ research apparatus successfully integrates preparation, performance testing, and characterization functions, with all mechanical, electrical, optical, and control systems fully commissioned to provide a reliable foundation for photocathode systematic studies. Using this apparatus, Cs₂Te photocathode preparation and its performance under various conditions were investigated, while in-situ GIWAXS characterization offered direct material-level evidence for structural evolution and process optimization; the structural and elemental evolution during photocathode degradation were also examined.

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