Technology Offer

Cavity-Enhanced Laser Heating of Reflective Samples under Ultra-High Vacuum

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Abstract

This innovative cavity-enhanced laser heating (CELAH) system delivers unparalleled efficiency for reflective samples in ultra-high vacuum (UHV) environments. Unlike traditional methods, such as resistive or electron bombardment techniques, this technology employs a laser-based system compatible with a wide range of wavelengths and materials, from highly reflective materials to semiconductors. At its core is a hemispherical optical cavity created by a polished concave reflector and the sample, which maximizes laser radiation utilization through multiple reflections, drastically increasing the energy transfer efficiency and achieving temperatures above 1400 K. This cost-effective, clean, and highly efficient heating technology provides precise thermal control for experimental and industrial applications, particularly in ultra-high vacuum environments and for reflective materials.

Background

Controlled temperature management of samples in UHV is crucial for surface science, material studies, and catalysis, where an atomically clean and stable environment enables precise analysis of surface phenomena. Conventional heating methods, such as resistive and electron bombardment heating techniques, often degrade UHV conditions through outgassing, contamination, and noise (compare Figure 1). Laser-based heating offers a cleaner alternative but is typically hindered by low absorption rates in metals and the need for high-power lasers, making such systems expensive and technically challenging. This new technology overcomes these limitations by employing a novel optical cavity design that maximizes heating efficiency. By dramatically improving energy transfer to reflective samples, it enables cost-effective, contamination-free heating across a broad range of materials while preserving UHV integrity.

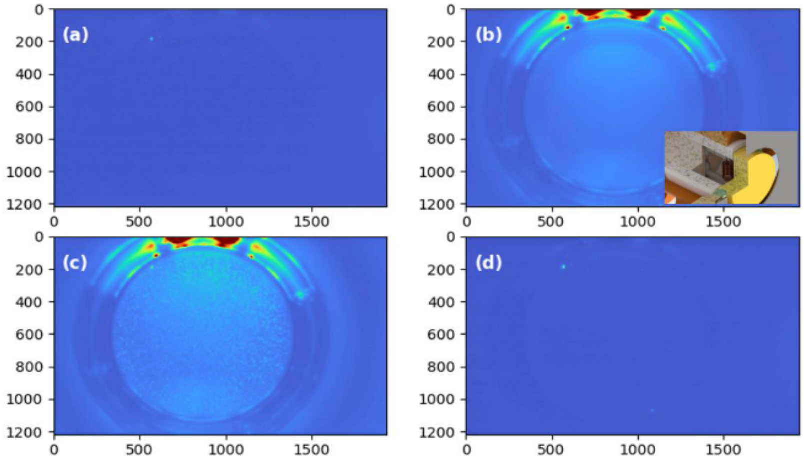

Figure 1: Example for raw background images of an ion imaging detector. All images show the summed intensity over two seconds. A graphite sample is located close to the detector (top edge of camera image) (a) Background image without any heating source. (b) Background for radiative heating using a tungsten filament at 2.2 A. The inset shows a cut of the respective sample holder. (c) Background with filament operated at 2.2 A and sample biased to 300 V for electron bombardment heating. (d) Background using a 26 W 455 nm heating laser impinging the front sample surface through the detector region.

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The system employs a concave reflector with a defined radius of curvature (ROC) to form a hemispherical optical cavity with the sample, coupled with a fiber-delivered laser, such as a 455 nm diode laser. The reflector ensures that light is retained within the cavity for multiple reflections maximizing the absorption of laser radiation by reflective samples. Simulations show that, under optimal alignment and cavity conditions (sample distance ≤ ROC), nearly all laser radiation can be confined within the system. Figure 2 provides an estimation of the maximum laser power absorbed by various sample materials, demonstrating how cavity enhancement dramatically improves efficiency for reflective materials like platinum. This design increases heating efficiency for metals like platinum from approximately 15% to 97%, representing a 6.4-fold improvement compared to single-reflection setups.

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This innovation enables efficient use of low-power lasers across a wide range of wavelength and materials. It supports rapid, safe heating to temperatures above 1400 K, while preserving UHV conditions and integrating seamlessly into experimental setups.

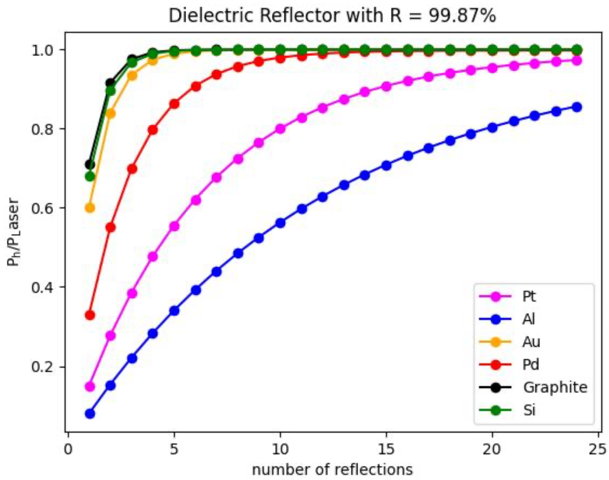

Figure 2: CELAH heating efficiency for different reflective (metals) and non-reflective (Si, Graphite) samples as function of reflections off the sample surface using a dielectric reflector with >99.8% reflectivity. In this configuration, almost all laser power can be provided as sample heating power.

Advantages

- Enhances Heating Efficiency: Reflective materials like platinum absorb up to 90% of laser radiation due to multiple reflections within the hemispherical optical cavity, a >6-fold improvement over single-reflection setups.
- Cost-Effective Design: Utilizes low-cost diode lasers (e.g., 455 nm models) instead of expensive high-power systems, significantly reducing investment and operational costs.
- Minimized Contamination: Maintains UHV integrity by eliminating outgassing and impurities from traditional heating filaments, ensuring clean experimental conditions.
- Rough conditions: Allows operation even under rough conditions like increase oxygen process pressures where hot filaments degrade rapidly.
- Rapid heating and response: selective heating of the sample which allows for high heating rates, laser can be pulsed on and off rapidly within few microseconds.

Potential applications

- Surface Science and Catalysis: Supports precise thermal control for studies on gas-surface interactions and catalytic reactions under UHV conditions.
- Material Research: Enhances processes like molecular beam epitaxy and atomic layer depositions by providing stable, contamination-free heating.
- Thin-Film Depositions: Improves the quality of thin films in semiconductor manufacturing by maintaining uniform heating and UHV conditions.
- Thermal Dynamics Studies: Enables investigations of temperature-dependent phenomena such as diffusion and phase transition in reflective materials.
- Sensitive Detection Systems: Reduces noise and contamination in ion imaging and spectroscopy experiments by eliminating filament emission.
- Graphene Growth on Silicon Carbide: Supports controlled heating processes for the thermal decomposition of silicon carbide, aiding in the production of graphene layers under UHV conditions.

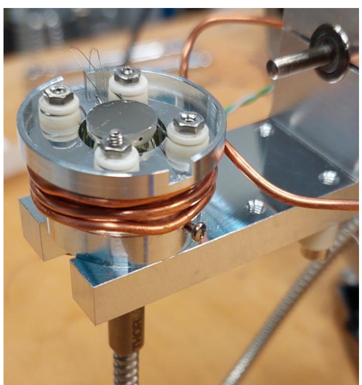

Figure 3: Photograph of the capsuled designed CELAH system.

Prototyping

The initial prototype featured an open design, while subsequent developments resulted in the capsuled prototype design shown in Figure 3. This configuration enhances laser radiation shielding, significantly improving overall safety. Additionally, the heating efficiency is increased due to the use of a commercially available dielectric mirror, which provide high reflectivity (compare Figure 4).

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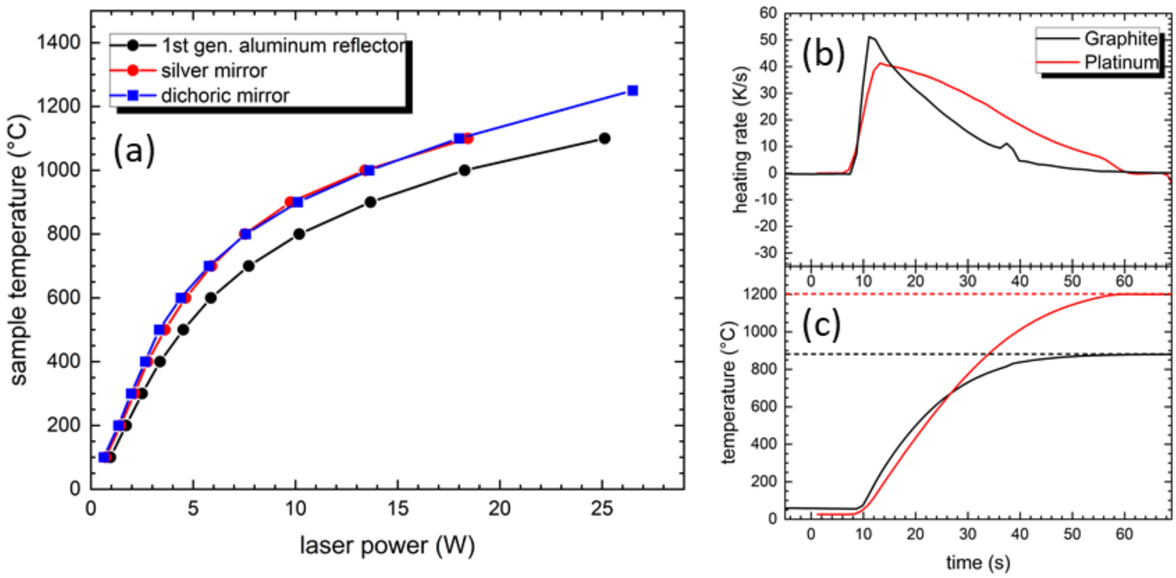

Figure 4: (a): Platinum sample temperature in dependence of the applied laser power for different CELAH system designs. (b) and (c): Heating rates for heating of platinum or graphite from room temperature to 1200°C and 900°C, respectively.

Furthermore, a prototype with integrated optical temperature measurement was developed measuring the sample temperature based on black body radiation emitted from the sample into the same fiber, which guides the heating laser beam to the sample. A beam splitter sends the radiation from the sample to a spectrum analyzer, for example a spectrometer or an array of bandpass filters with suitable photon detectors. Additionally, the prototype enables an online laser power measurement. The setup is shown schematically in Figure 5.

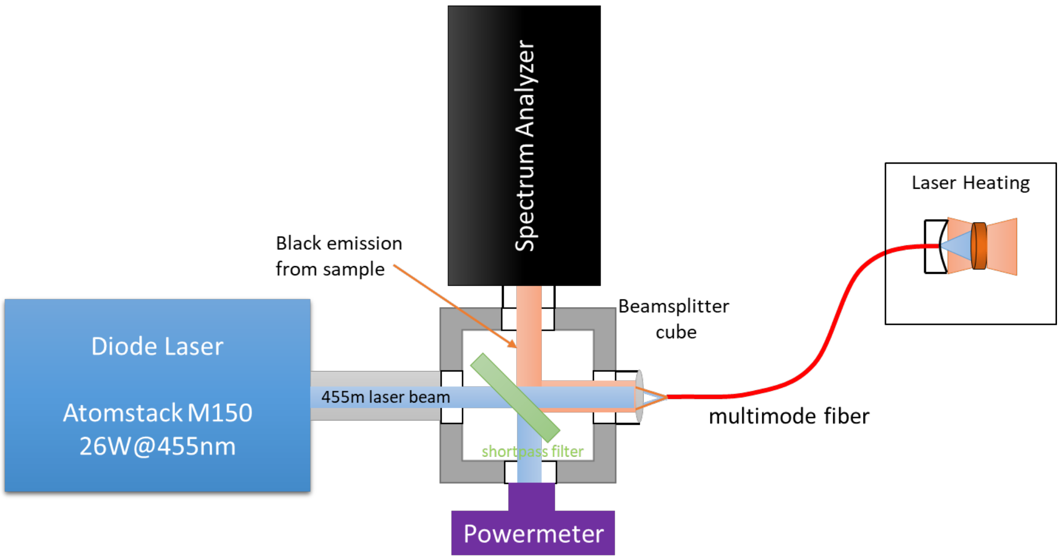

Figure 5: Scheme of the laser heating system with integrated optical temperature measurement and online tracking of the laser power.

Patent Information

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