Development and characterization of a laser-driven cold-field emission source

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Background

Ultrafast transmission electron microscopy (UTEM) utilizing pulsed electron sources, has emerged as a crucial tool for probing ultrafast dynamics at the nanoscale. Recent breakthroughs in laser-driven Schottky electron emitters have significantly enhanced the spatial and temporal coherence of electron pulses, achieving temporal pulse widths below 200 fs and electron spot sizes as small as 1 nm [1]. The potential for further enhancement in pulse coherence is anticipated through the application of laser-driven cold-field emitters, especially when operated in a linear photoemission regime [2].

Methods

Here, we present the development and characterization of a long-term-stable laser-driven cold-field emitter source, designed for advanced ultrafast transmission electron microscopes and operating at 200 keV electron energy [3]. Based on a JEOL cold-field emitter gun (CFEG), the source utilizes a sharp single-crystalline (310) tungsten tip within a vacuum level of 10^-12 to 10^-11 mbar. For pulsed operation, the source is modified to allow for a direct optical line-of-sight onto the emitter through opposing optical entrance windows.

Results

In the initial implementations, we conducted a comprehensive characterization of the photoemission yield from the tip using a continuous-wave optical illumination at 3.59 and 3.06 eV photon energy focused to a 20 µm scale spot on the emitter apex (Fig. 1c, right inset). Notably, the employed photon energy is below the work function of tungsten so that linear photoemission is only feasible at the apex of the tip which exhibits a Schottky-reduced effective workfunction. Continuous field emission, following a Fowler-Nordheim description, is observed at large electric extraction fields without illumination (blue curve in Fig. 1b). Illumination at 1 mW optical power reveals an additional photoelectron contribution at low extraction field values, for which continuous field emission is absent (yellow and red curves in Fig. 1b). The onset of photocurrents is dependent on the photon energy of the illuminating light field. Above this threshold the current scales linearly with light intensity (Fig. 1c). Notably, under extreme high vacuum (XHV) conditions near the emitter, no significant drop in photoemission yield is observed over a 10-hour period (Fig. 1c, left inset).

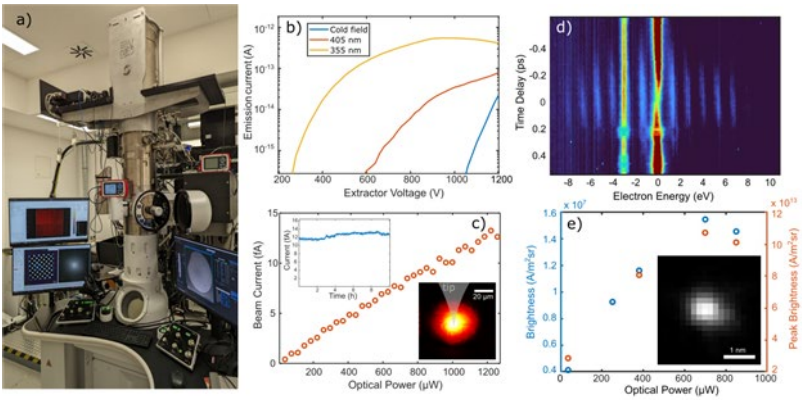
In a subsequent step, the emitter is operated as part of the Regensburg JEOL F200 UTEM (Fig. 1a), using ultrashort laser pulses with a duration of 200 fs at a central wavelength of 345 nm. We systematically carried out an extensive pulse characterization, including the pulsed electron energy distribution, pulse duration, and the spatial attributes of electron brightness across varied excitation fields.

When operated at a state in which both, field- and photoemission can occur, the final kinetic energy of electron generate by the two emission processes are needly separated (Fig. 1d). Performing an electron-photon cross correlation we obtain 300 fs-electron pulse duration and energy width of about 300 meV.
Remarkably, our findings reveal that focal sizes of below 0.74 nm and a normalized peak brightness of 10^14 A/m^{2}sr (Fig. 1e) can be achieved, surpassing the brightness of the laser-driven Schottky field emitter constructed in our lab by an order of magnitude. Currently, small electron focal spot sizes are limited to a low current-regime, due to the onset of spherical aberration at larger convergence angles. It should be possible to further improve the transversal beam properties at higher pulse charges utilizing a probe aberration corrector.

Conclusion

In conclusion, we demonstrate the successful development of a stable, laser-driven cold-field emitter source for ultrafast transmission electron microscopy applications. Our findings illustrate the potential to significantly enhance electron beam brightness and reduce energy spread of electron pulses, paving the way for further advancements in probing ultrafast dynamics at the nanoscale.

Graphic:



Keywords:

UTEM
Electron-pulse
Laser-driven
Cold-field-Emitter

Reference:

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[2] F. Houdellier et al., Ultramicroscopy 186, 128 (2018).
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