
Supplementary information

**High-endurance micro-engineered LaB₆
nanowire electron source for high-
resolution electron microscopy**

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High-endurance Micro-engineered LaB₆ Nanowire Electron Source for High-resolution Electron Microscopy

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1. Angular control by collimator tip structure:

The axial deviation angle correction effect of the collimator structure is demonstrated in extended data figure 1. In this example, two support needles of the same 4 μ m diameter were compared: one with a collimator structure and one without. Nanowire suspension length were also similar, $\sim$ 2 μ m. Both nanowires were aligned perfectly with optical axis. Field emission pattern shows that bare tip produced 5.4° deviation angle while the deviation angle of the collimator structure is within 1°. We also did FEM simulation using SIMION software (Extended data figure 1a, b) to examine the effect of nanowire suspension length on the axial deviation angle. The result is summarized in extended data figure 1c. More than 80% axial deviation angle reduction for the collimator structure is expected especially with short nanowire suspension length below 1 μ m. It is noted that the collimator front surface was not perfectly perpendicular to optical axis, but with a 4° tilting angle due to fabrication imperfection. Even under this condition, simulation shows that deviation angle lower than 1° could be guaranteed for a collimator structured nanowire emitter.

Simulation method: 3D model of support needle was assigned with equal potential at -300V while space boundary was assigned with 0V. For each nanowire suspension length, a potential drop ΔV was calculated at the position of nanowire

apex. Electrons were freed at the apex position with assumed initial energy of ΔV and initial speed vector aligned with the nanowire axis towards ground potential. Electron trajectory interception point with ground boundary was thus calculated and form a trajectory line by connecting to the nanowire apex. The angle between the nanowire axis and such trajectory line is defined as the axial deviation angle.

2. Determination of spatial frequency associated with linear contrast transfer:

A Titan3 microscope (FEI) equipped with a high-brightness Schottky emission gun (X-FEG) and tandem spherical aberration correctors (DCOR and CETCOR, CEOS) was used at an accelerating voltage of 80 kV. With a 0.2eV-monochromated electron gun, we could produce a chromatic envelop with a very similar shape to that predicted for LaB₆ NW electron gun at 60kV. (plotted as a red curve in extended data figure 4a) A high resolution TEM image was taken on Si (110) specimen with the monochromator in the on state. A second TEM image was taken with exactly the same condition but with the monochromator in the off state. (Extended data figure 3) In this case, the intrinsic high energy spread of Schottky emitter (0.8eV) results in a chromatic envelop with a much shorter transfer range, as plotted as a blue curve in extended data figure 4a. Extended data

figure 4b is a comparison between diffractograms from each TEM images. It showed clearly that the three spots of (115), (224) and (333) reflections in red circles appeared as additional spots in the monochromated TEM image. Therefore, these three spots are identified as a result of linear contrast transfer process, where information was limited only by chromatic damping envelop. Therefore, (115) and (224) spots with spacings of 105pm and 110pm were chosen to compare contrast transfer amplitude between LaB₆ NW TEM and W (310) TEM. (333) spot was not chosen because of both its lower intensity in figure 6b and its being inseparable from influence of secondary interference between reflections of (111) and (222).

3. Emission area validation:

LaB₆ NW emitter: The Fowler-Nordheim equation fitting predicts areal current density $4.4 \times 10^8 \text{ A/m}^2$ for the data point with 48pA probe current, 0.23eV ΔE , and 1nA total emission current. A total emission area of 2.36 nm^2 was then estimated through dividing total current by areal current density. Extended data figure 10b is a field emission microscopy pattern about the LaB₆ NW (100) facet. With size calibration using field ion microscopy pattern of extended data figure 10a, we

could obtain the emission area in extended data figure 10b to be 2.69nm^2 . This emission area measurement value is 14% different from that estimated through Fowler-Nordheim equation fitting.

W (310) emitter: The Fowler-Nordheim equation fitting predicts areal current density $4.4 \times 10^9 \text{ A/m}^2$ for the data point with 1340pA probe current, 0.39eV ΔE , 3.91kV extraction voltage and 6400nA total emission current. A total emission area of 1412nm^2 was then estimated through dividing total current by areal current density. Extended data figure 10d is a field emission microscopy pattern about the W (310) facet. With size calibration using field ion microscopy pattern of extended data figure 10c, we could obtain the emission area in extended data figure 10d to be 36.8nm^2 . Note that this emission pattern was obtained with a sharp (110) W needle producing similar current density with the W (310) emitter at extraction voltage of 700V (1). It indicates a radius of curvature 18% that of the W (310) emitter under the current study. If we assume emission area scales with square of tip radius, we could estimate emission area for the W (310) emitter to be 1150nm^2 , which is 23% different from that estimated through Fowler-Nordheim equation fitting.