

Supplementary Information

**XeF₂ Gas Assisted Focused Electron Beam Induced Etching of Niobium Thin Films: Towards
Direct Write Editing of Niobium Superconducting Devices**

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SI Section 1. XeF₂ gas-assisted FEBIE box etches of Nb films

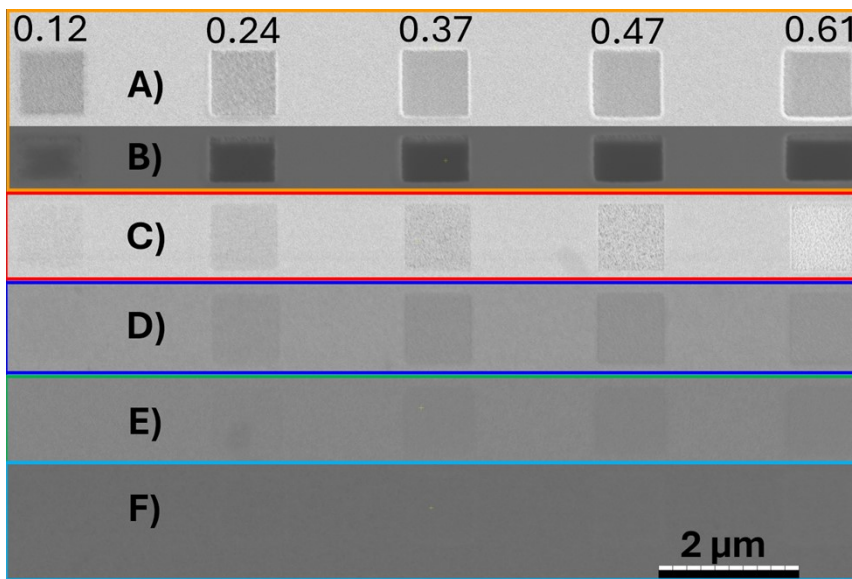
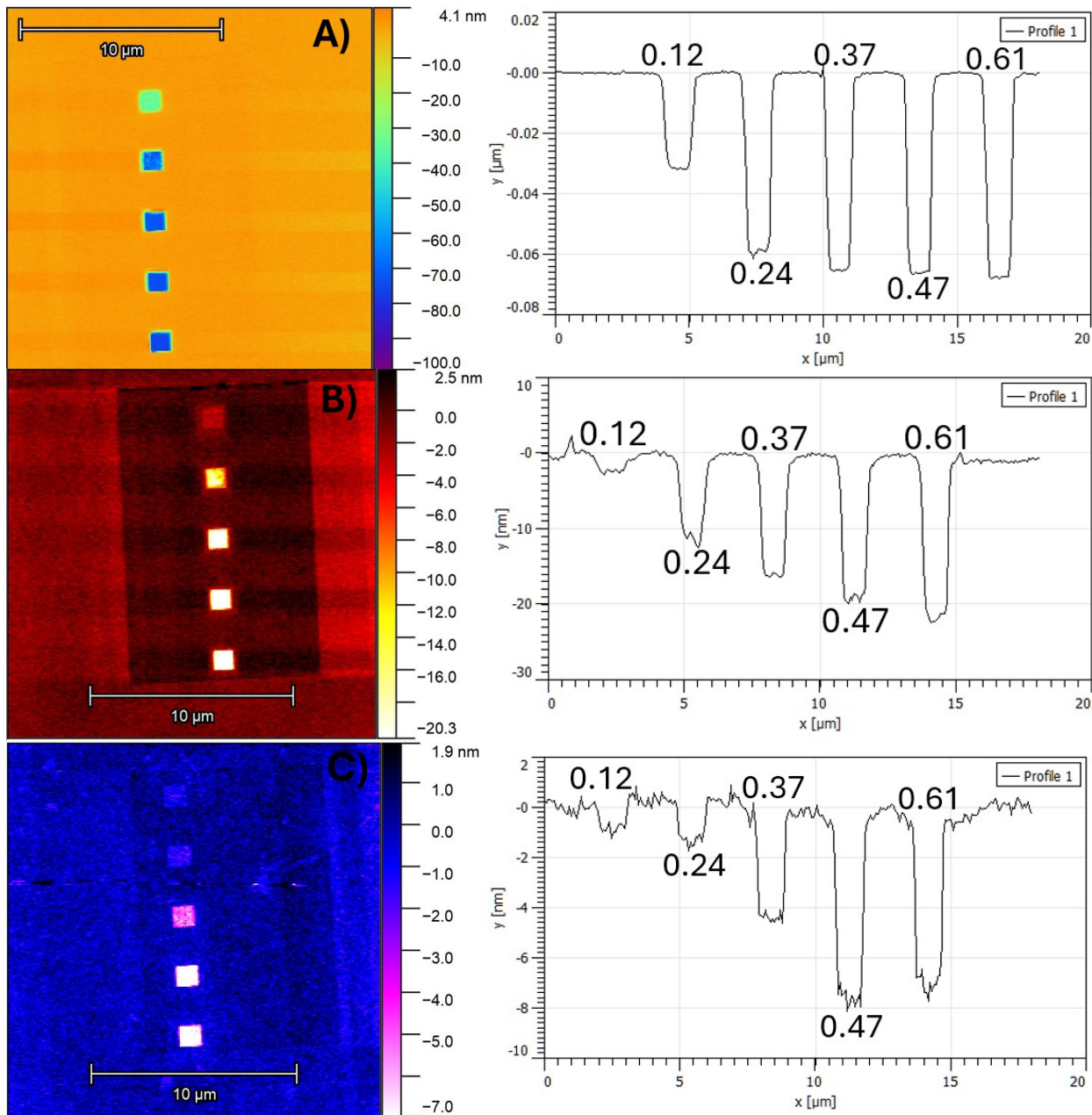


Figure S1. SEM images of 1 μm² gas-assisted FEBIE box etches at a beam energy of 1 keV, dwell time of 1 μs, pixel pitch of 10 nm, XeF₂ working pressure of 1x10⁻⁵ Torr for beam currents of, a) 0.025 nA with tilted photo at b) 52°, c) 0.1 nA, d), 0.2 nA, e) 0.4 nA, and f) 0.8 nA.



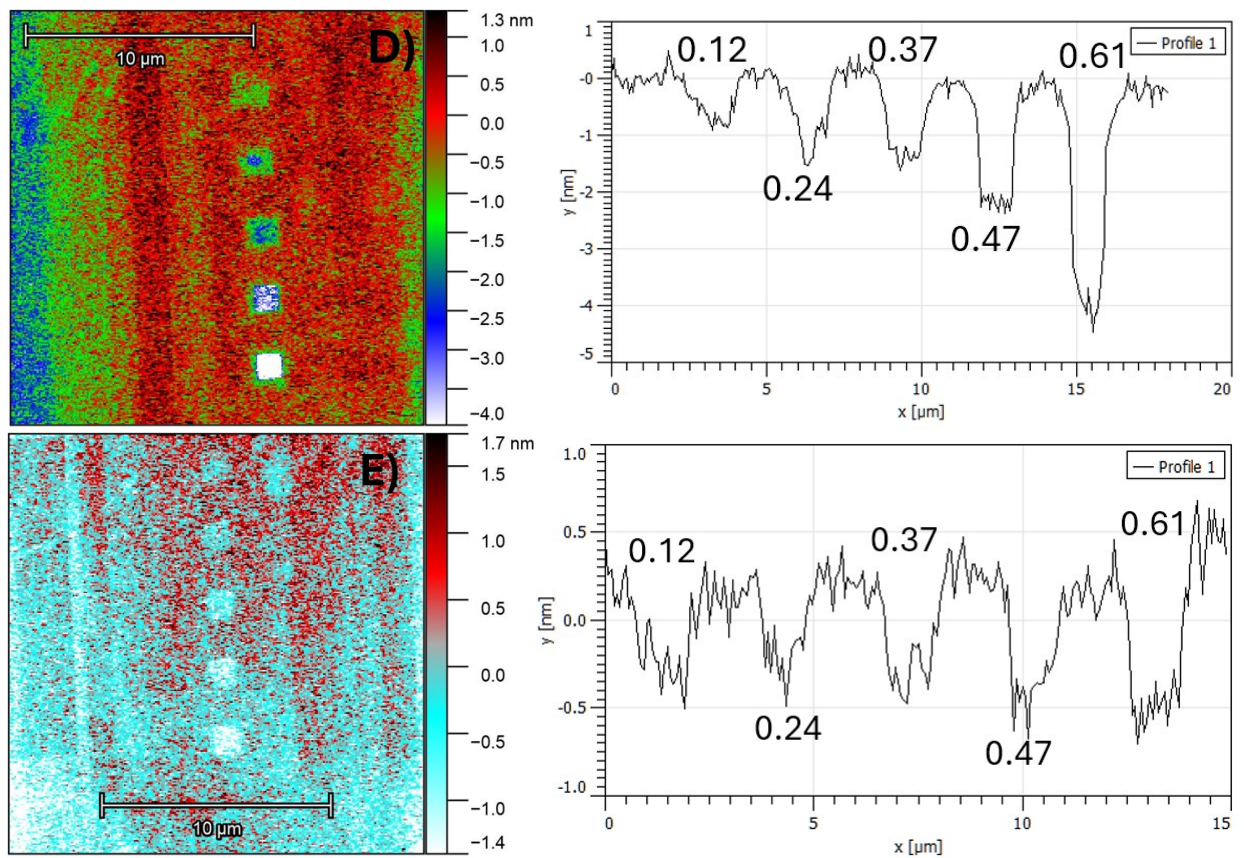


Figure S2. AFM images and profile graphs of $1 \mu\text{m}^2$ gas-assisted FEBIE box etches at a beam energy of 1 keV, dwell time of $1 \mu\text{s}$, pixel pitch of 10 nm, XeF_2 working pressure of 1×10^{-5} Torr for beam currents of, a) 0.025 nA, b) 0.1 nA, c) 0.2 nA, d) 0.4 nA, and e) 0.8 nA for doses of 0.12, 0.24, 0.37, 0.47, and 0.61 $\text{nC}/\mu\text{m}^2$.

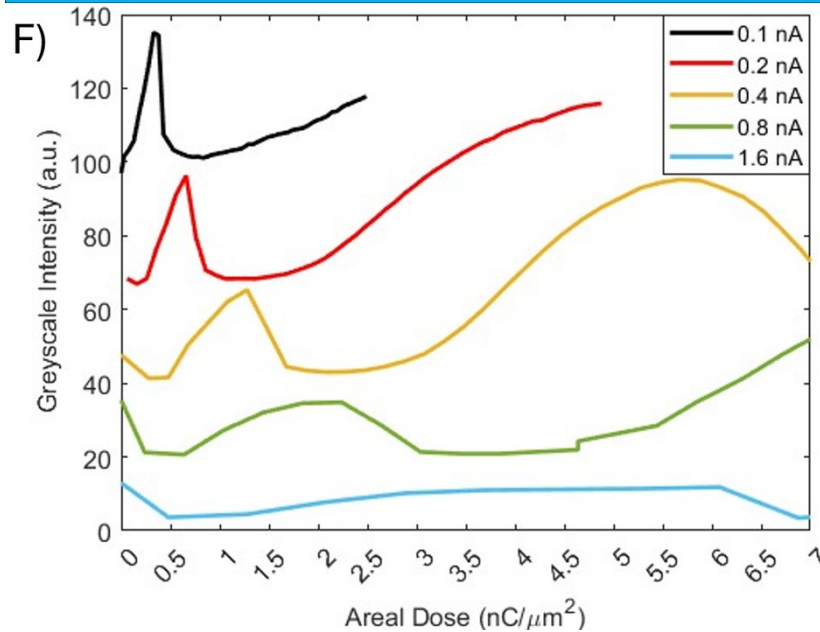
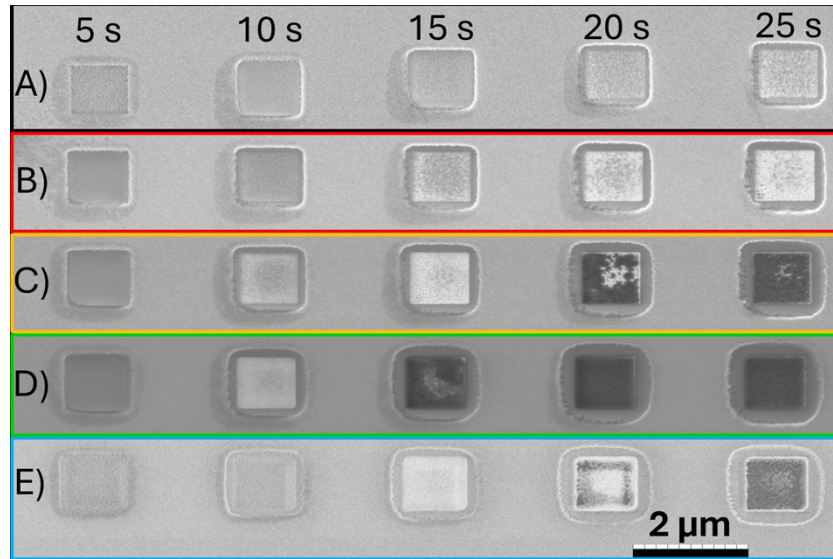


Figure S3. Gas-assisted FEBIE of 1 μm² box etches were conducted at a beam energy of 1 keV, dwell time of 1 μs, pixel pitch of 10 nm, XeF₂ working pressure of 3x10⁻⁵ Torr. SEM images were taken for boxes etched at beam currents of a) 0.1 nA, b) 0.2 nA, c) 0.4 nA, d) 0.8 nA, and e) 1.6 nA. EPM graphs of these etches were all plotted in f) and every EPM for the 0.2 nA series are plotted over one another in g).

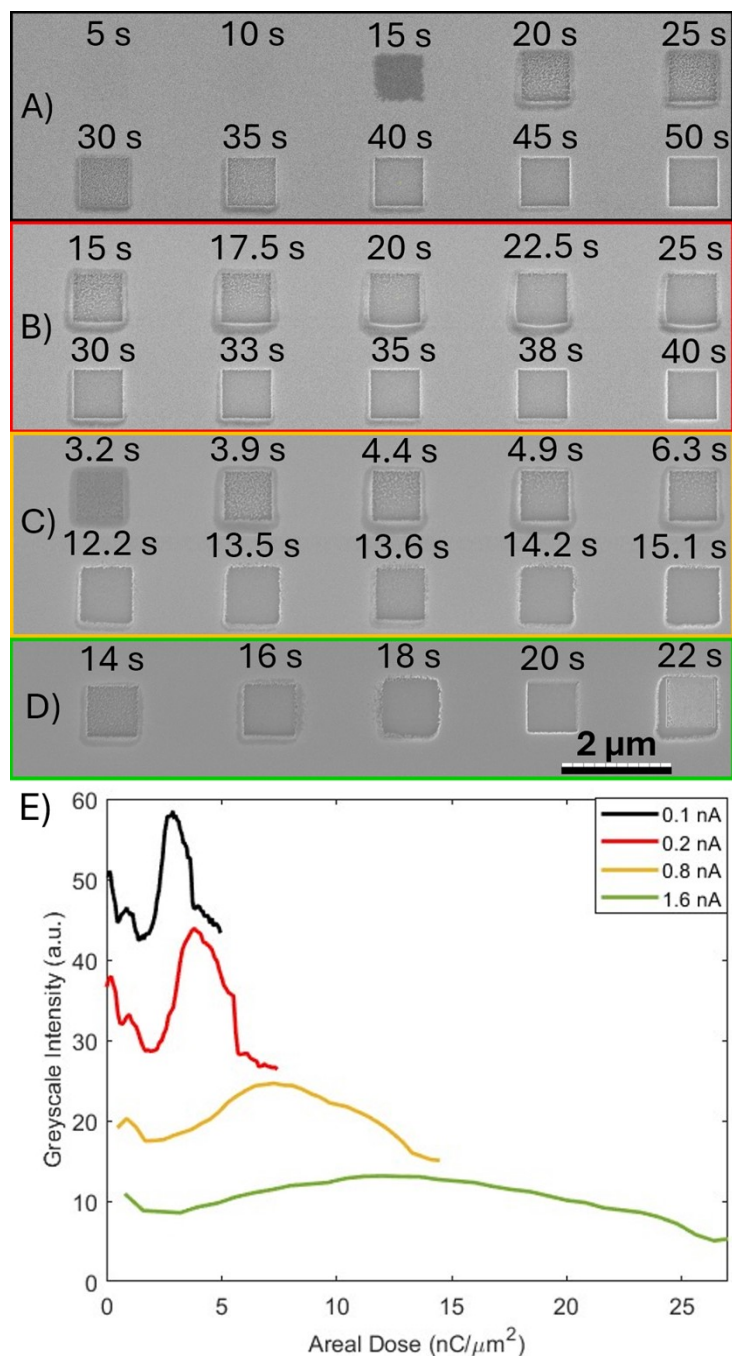


Figure S4. Gas-assisted FEBIE of $1 \mu\text{m}^2$ box etches were conducted for a beam energy of 20 keV, dwell time of $0.025 \mu\text{s}$, pixel pitch of 10 nm, XeF_2 working pressure of 4.7×10^{-6} Torr, for beam currents of; a) 0.1 nA, b) 0.2 nA, c) 0.8 nA, and d) 1.6 nA. EPM graphs of these etches were all plotted in e).

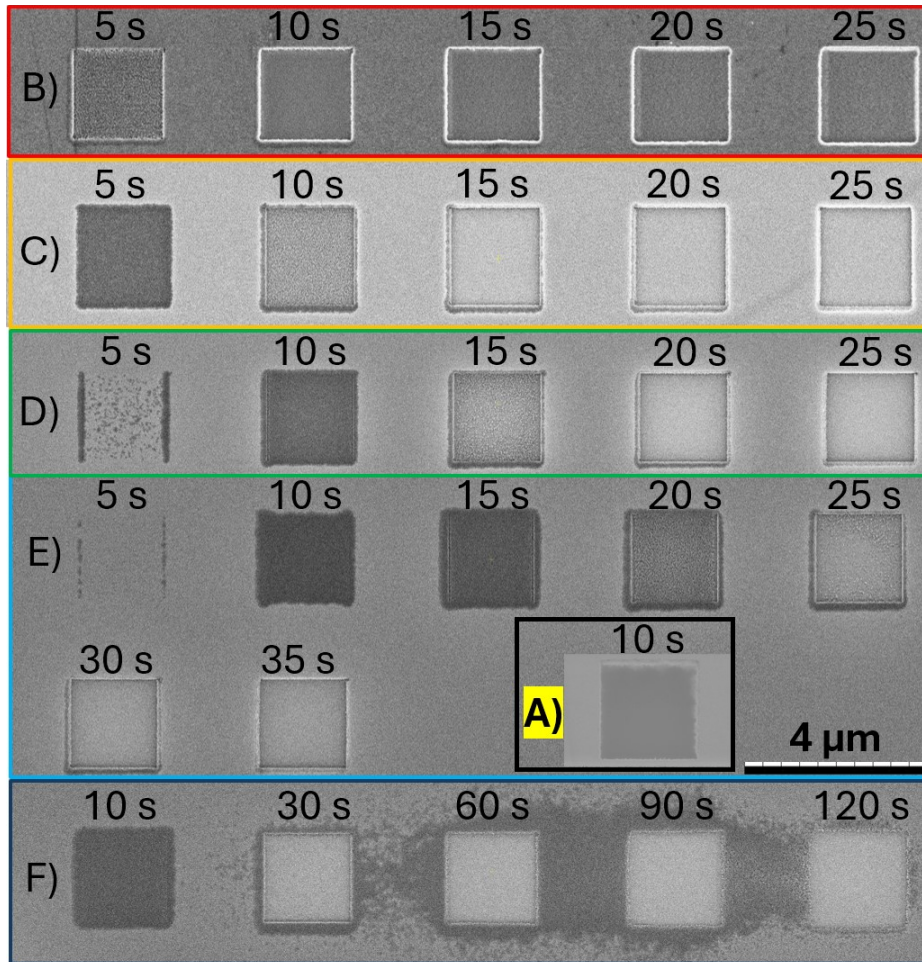


Figure S5. SEM images for of gas-assisted FEBIE of $4 \mu\text{m}^2$ box etches for a beam current of 0.1 nA, dwell time of $0.025 \mu\text{s}$, pixel pitch of 10 nm, XeF_2 working pressure of 1×10^{-5} Torr, for beam energies of; a) inset of 0.5 keV, b) 1 keV, c) 5 keV, d) 10 keV, e) 15 keV, and f) 10 keV.

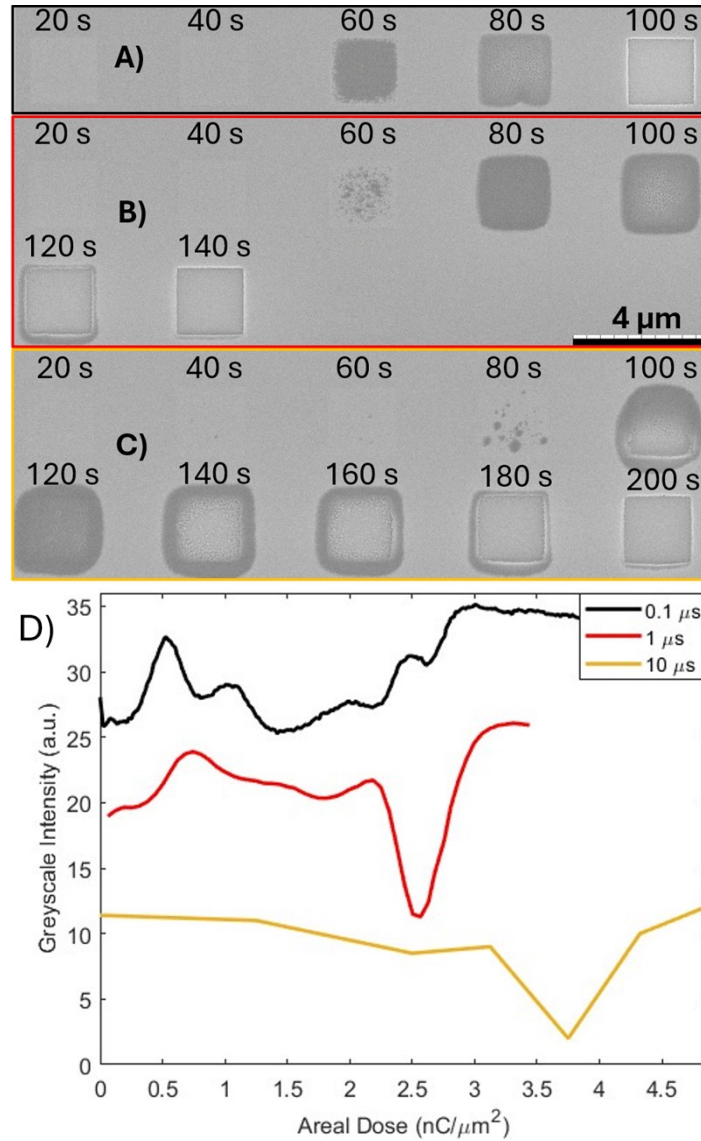


Figure S6. SEM images (left) and end-point-monitor graphs (right) of gas-assisted FEBIE of 4 μm^2 boxes at a beam energy of 20 keV, beam current of 0.1 nA, pixel pitch of 10 nm, XeF_2 working pressure of 1×10^{-5} Torr, at dwell times of a) 0.1 μs , b) 1 μs , and c) 10 μs .

SI Section 2. XeF_2 gas-assisted FEBIE line etches of Nb films

SI Section 3. XeF_2 gas-assisted FEBIE statistics

Table SI. XeF_2 flux from GIS to eucentric position at various flow rates used for line etching

XeF_2 working pressure (Torr)	Equilibrium Flux ($\text{XeF}_2/\text{cm}^2 \text{ s}$)	Localized Flux ($\text{XeF}_2/\text{cm}^2 \text{ s}$)
1.15E-05	1.79E+15	2.66E+18
8.48E-06	1.32E+15	1.96E+18
5.93E-06	9.25E+14	1.37E+18
2.67E-06	4.17E+14	6.19E+17

1.04E-06	1.62E+14	2.41E+17
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Table SII. Summary etch statistics for spontaneous box area study

Box Area (um ²)	Gas flux (XeF ₂ /nm ² -s)	Electron flux (e-/pixel-s)	Electron Areal Dose per pixel area, per dwell (e-/100 nm ²)	XeF ₂ monolayers per refresh	Ratio e-/XeF ₂	Nb atoms etched/e ⁺
0.25	2.32E+04	1.25E+09	859.42	0.49	1.48E+00	0.11
1	2.32E+04	1.25E+09	922.95	1.96	7.82E-01	0.22
4	2.32E+04	1.25E+09	986.49	7.86	8.36E-01	0.42
16	2.32E+04	1.25E+09	1050.03	31.43	8.90E-01	0.59
64	2.32E+04	1.25E+09	1113.56	125.72	9.44E-01	0.79