Gallium Nitride Micro-Pyramids as Coating-Free Negative Electron Affinity Photocathodes

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Bright electron sources are essential for high-resolution nanofabrication, metrology, and imaging. Caesiated semiconductor photocathodes provide high quantum efficiency and exceptional versatility for temporal control and multi-beam systems [1,2]. However, their operational lifetime is severely limited by degradation of the cesium layer over time and subsequent loss of Negative Electron Affinity (NEA) [3]. This work introduces a novel virtual-source photocathode that leverages intense field concentration at the apex of p-doped gallium nitride (GaN) micro-pyramids to achieve NEA without surface coatings.

Micro-pyramid arrays are fabricated on free-standing GaN substrates via a scalable, top-down process based on grayscale lithography (Fig. 1a). The ~1 μm apex radius of each pyramid facilitates geometric enhancement of an external electric field. Finite element method simulations predict that at field strengths of ~1 GV/m, the vacuum barrier is lowered below the conduction band minimum while the surface remains electron-depleted (Fig. 1b). This regime enables efficient laser-controlled emission via near-bandgap photoexcitation.

The model is validated by testing single micro-pyramids in a dedicated photo-field emission setup integrated within a scanning electron microscope (Fig. 2). A distinct operational range is identified, strictly governed by the electric field strength, where electron emission occurs exclusively under photoexcitation (Fig. 3a). Within this regime, the current scales linearly with laser power (Fig. 3b), up to values exceeding 15 nA. At higher field strengths, the transition to dark field emission is observed, reaching currents above 10 μA.

By eliminating caesiation and leveraging a mature semiconductor platform, this technology is uniquely suited for high-throughput nanofabrication and imaging. The geometry ensures a source size comparable to conventional point cathodes, yielding similar brightness, while top-down fabrication enables large-scale multi-beam architectures. These field-induced NEA emitters represent a robust and versatile solution for the next generation of focused electron beam equipment.

[1] D. Sato *et al.*, Journal of Vacuum Science & Technology B **40**, (2022).
[2] D. Sato *et al.*, Journal of Vacuum Science & Technology B **39**, (2021).
[3] T. Nishitani *et al.*, Journal of Vacuum Science & Technology B **32**, (2014).
[4] R. H. Fowler and L. Nordheim, Proceedings of the Royal Society A **119**, (1928).

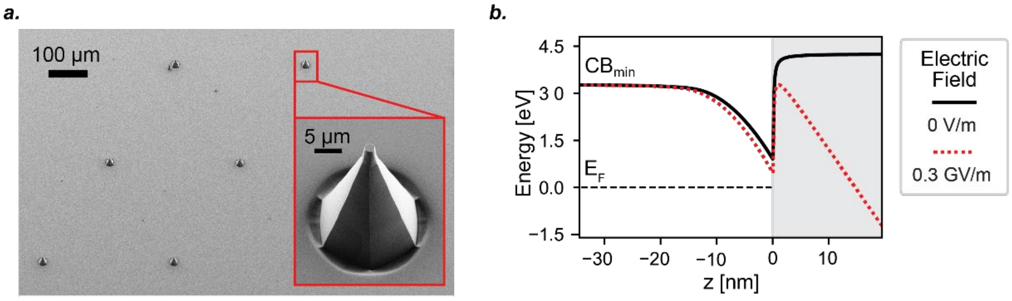

Figure 1: Field-induced NEA in GaN micro-pyramids. ***a.*** SEM of a GaN micro-pyramids array. ***b.*** Finite element method simulations of the potential barrier at the GaN-vacuum interface (z = 0 nm). CB_{min}: conduction band minimum, E_F: Fermi Level.

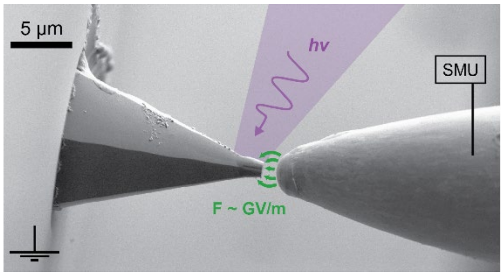

Figure 2: Experimental setup. A 3.49 eV ultrafast laser is focused into a ~6 μm spot at a micro-pyramid apex, while a biased micro-manipulator applies a variable external field (F). hν: photon energy; SMU: source measurement unit.

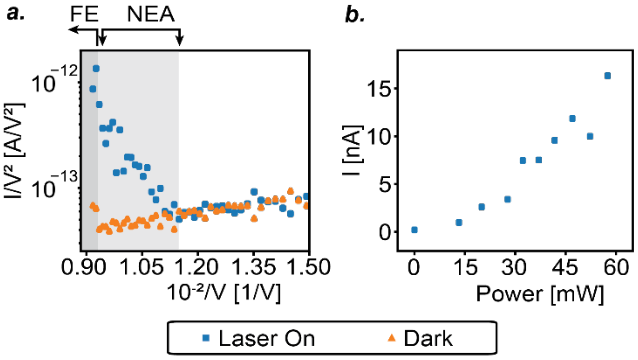

Figure 3: Electron emission characteristics of a single micro-pyramid. ***a.*** Fowler-Nordheim [4] plot t – ln(I/V2) versus 1/V, where I is the emitted current and V the micro-manipulator voltage (proportional to the field strength) – comparing dark conditions and 4 mW laser illumination at a micro-pyramid-to-micro-manipulator distance of 0.25 μm. ***b.*** Emitted current I as a function of incident laser power at a fixed bias of 200 V and a distance of 0.55 μm, showing the linear photoemission regime. FE: Field Emission.