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Nano-diamond emitters: a little bit of everything

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Acknowledgments

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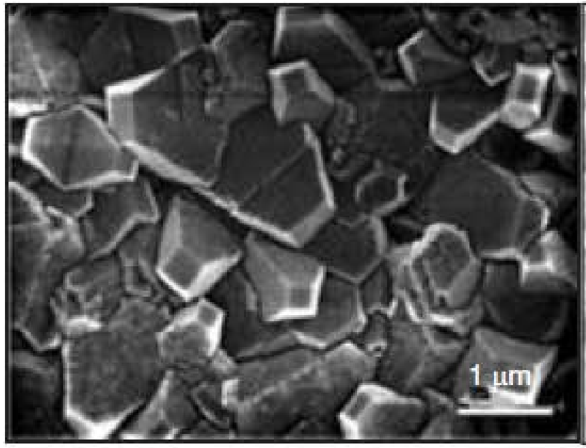
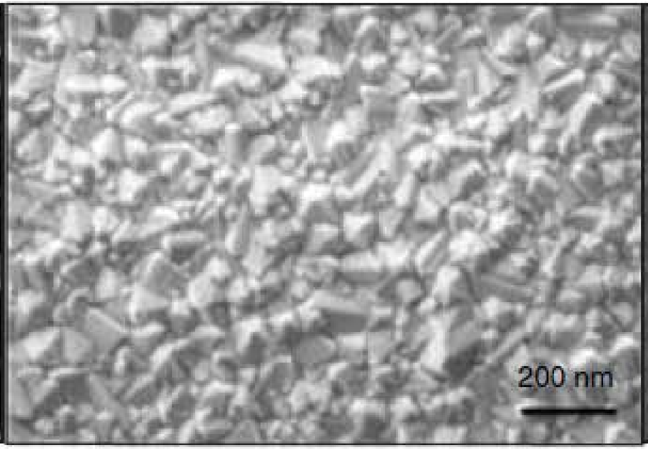
Drs. Robert Rechenberg and Michael Becker, Fraunhofer USA

Ultra-nano-crystalline diamond

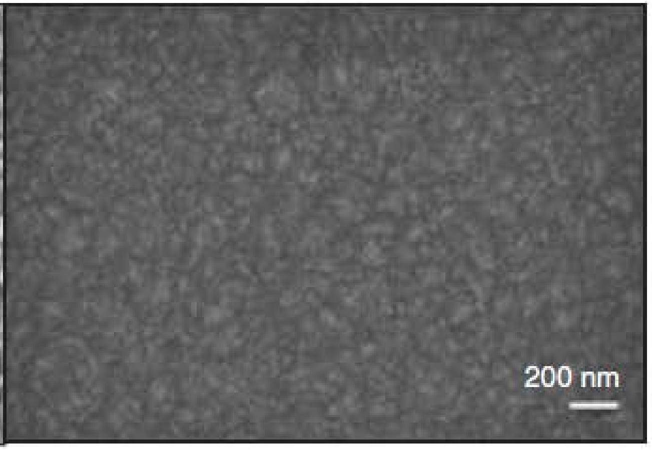
Microcrystalline:
dia. grain ≥500 nm

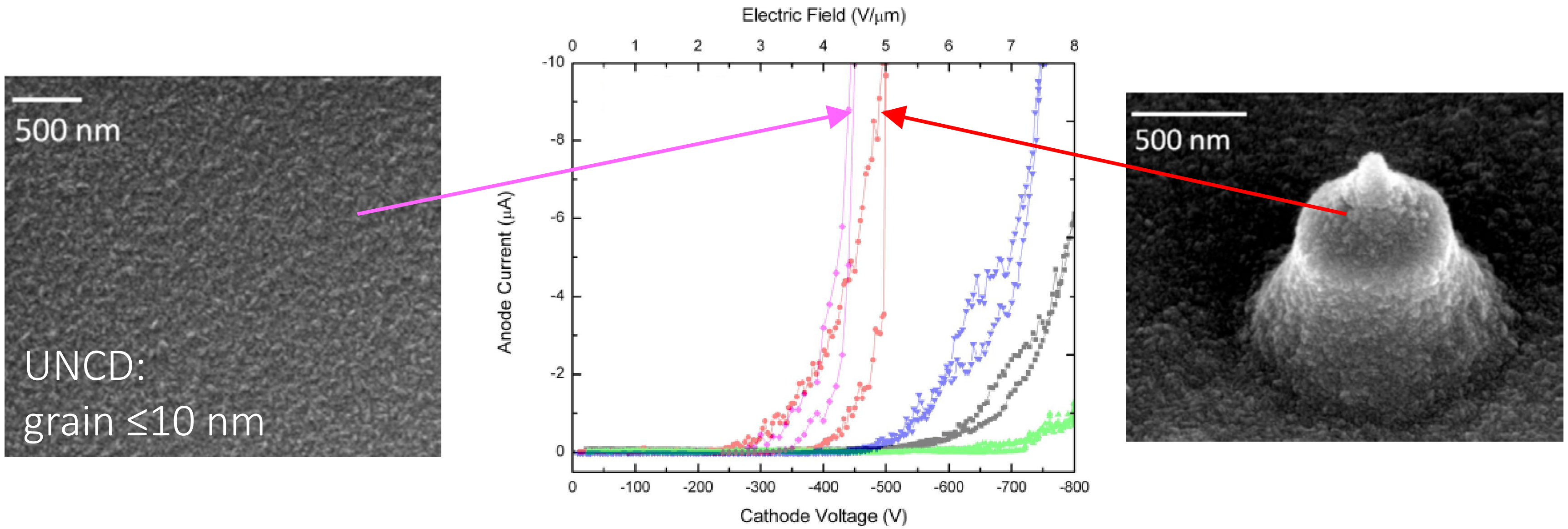


Nanocrystalline:
dia. grain 10-200 nm



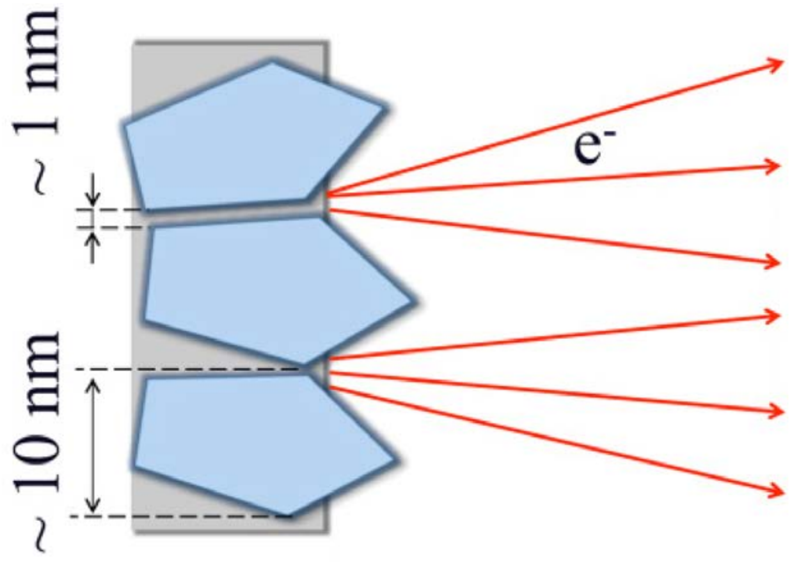
UNCD:
dia. grain ≤10 nm



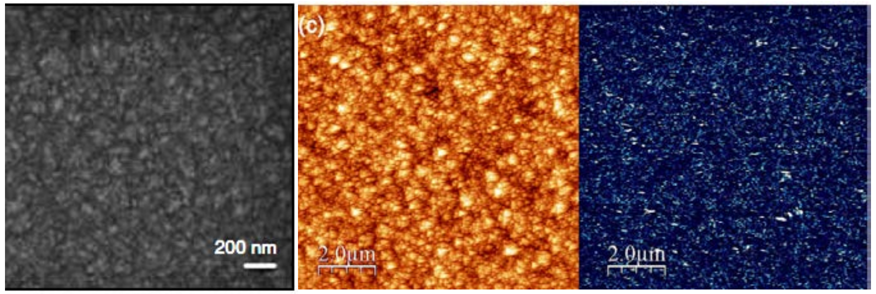


MRS Bulletin **35**, 281 (2010); Proc. SPIE **7679**, 76791N (2010)

Importance of grain boundaries



Field- and photo- emission data is consistent:
sp^2 grain boundaries (GBs) emit electrons

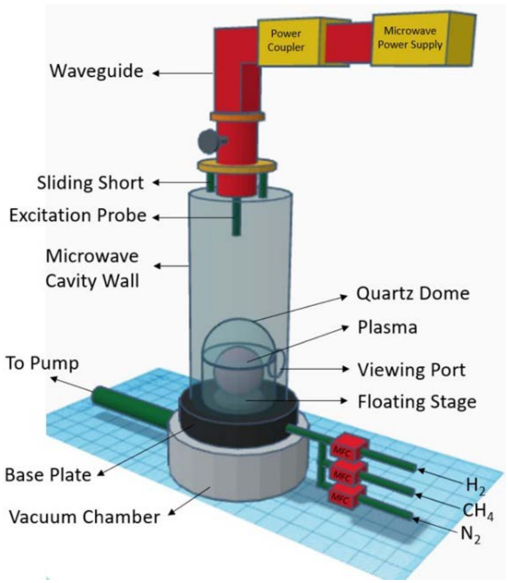


PRB **60**, 16135 (1999);Carbon **94**, 386 (2015)

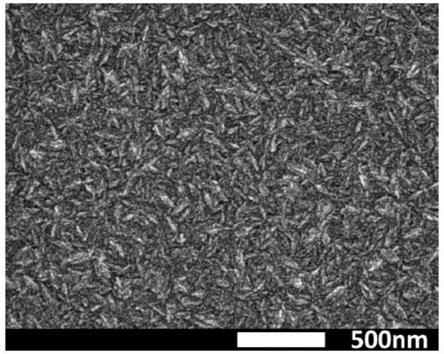
Electron transport is also through *sp*^{2} GBs:
$m^* \approx 1/18m_0$
PRB **82**, 184206 (2010)

(N)UNCD synthesis and basic characterization

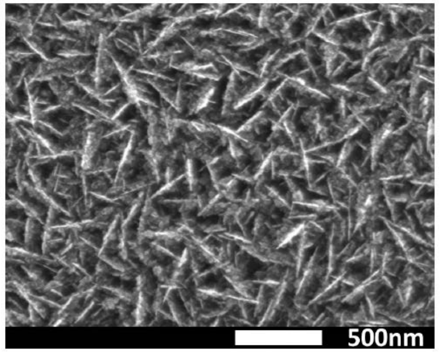
Microwave-assisted plasma chemical vapor deposition: DS5@2.45 GHz, the queen mother of MWCVD systems



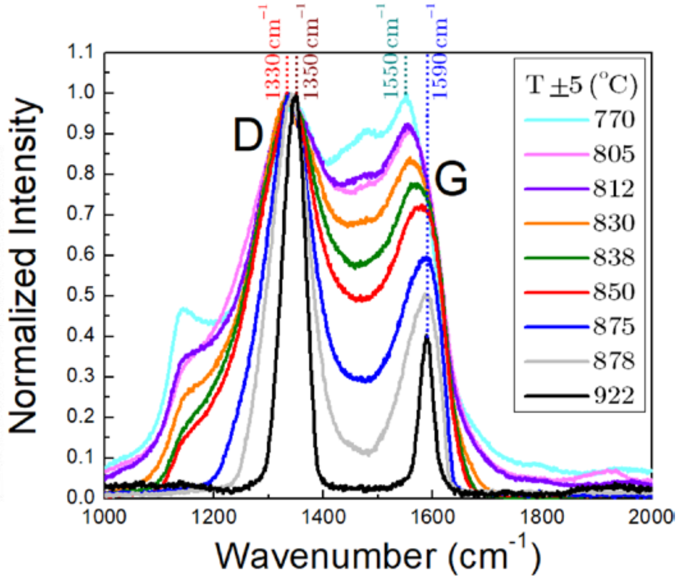
(N)UNCD viewed by SEM, Raman and electrical measurements

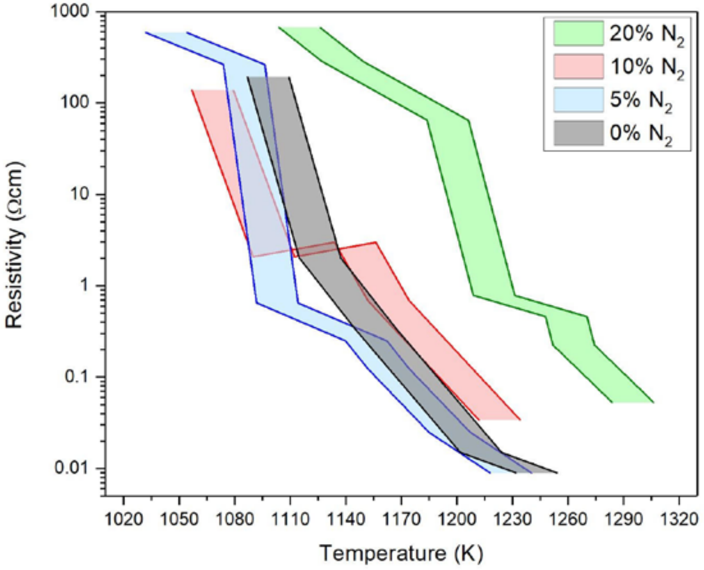


(a) SC2: T_d=1101 K



(c) SC5: T_d=1223 K

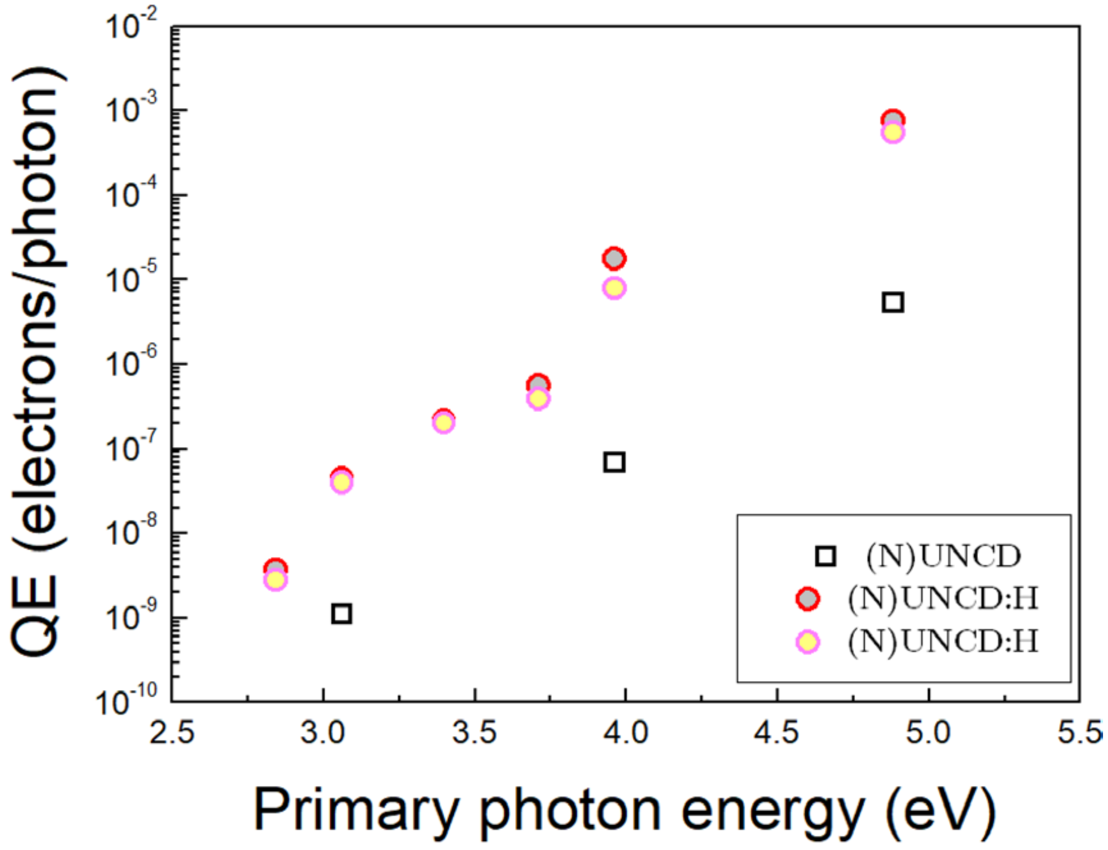


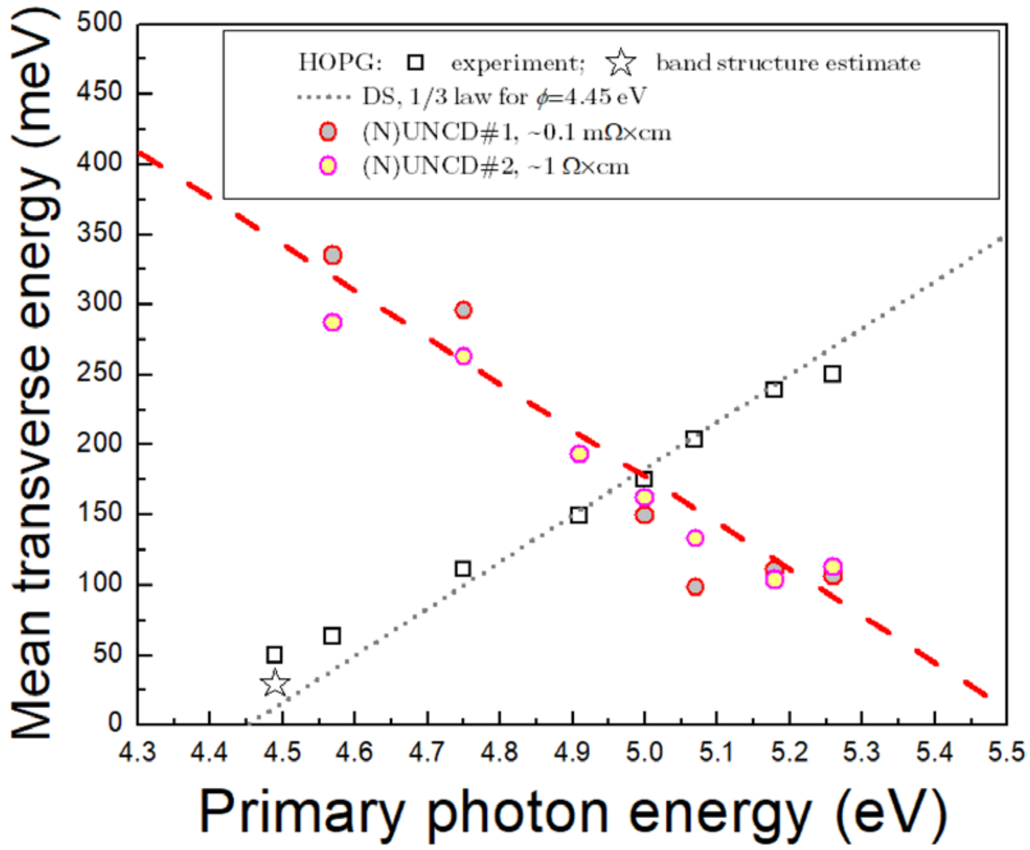


Beyond Dowell-Schmerge law

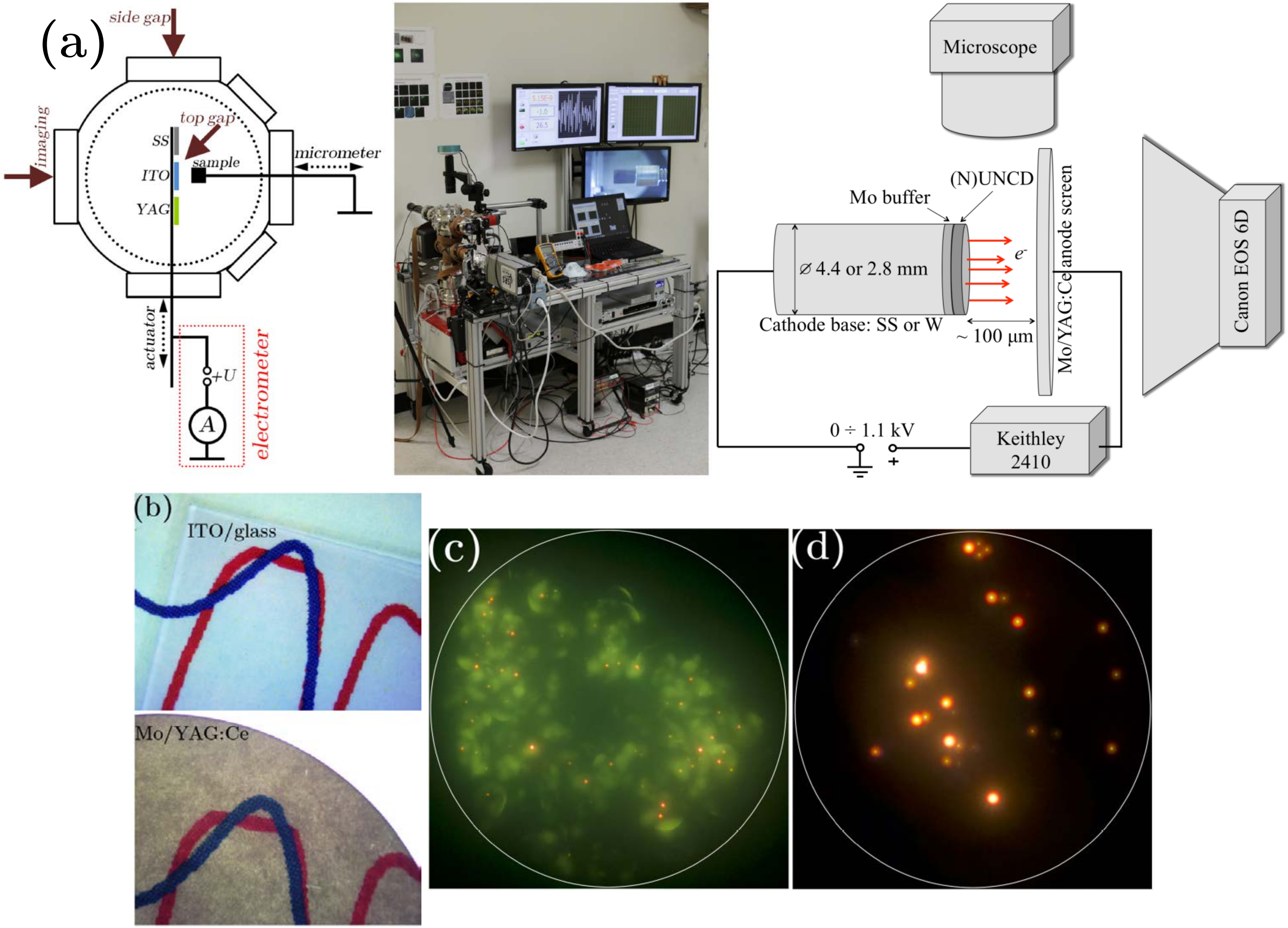
Anti-Dowell photocathode (coined by WA Schroeder):

high increasing QE and low decreasing MTE is a route to brighter photocathodes



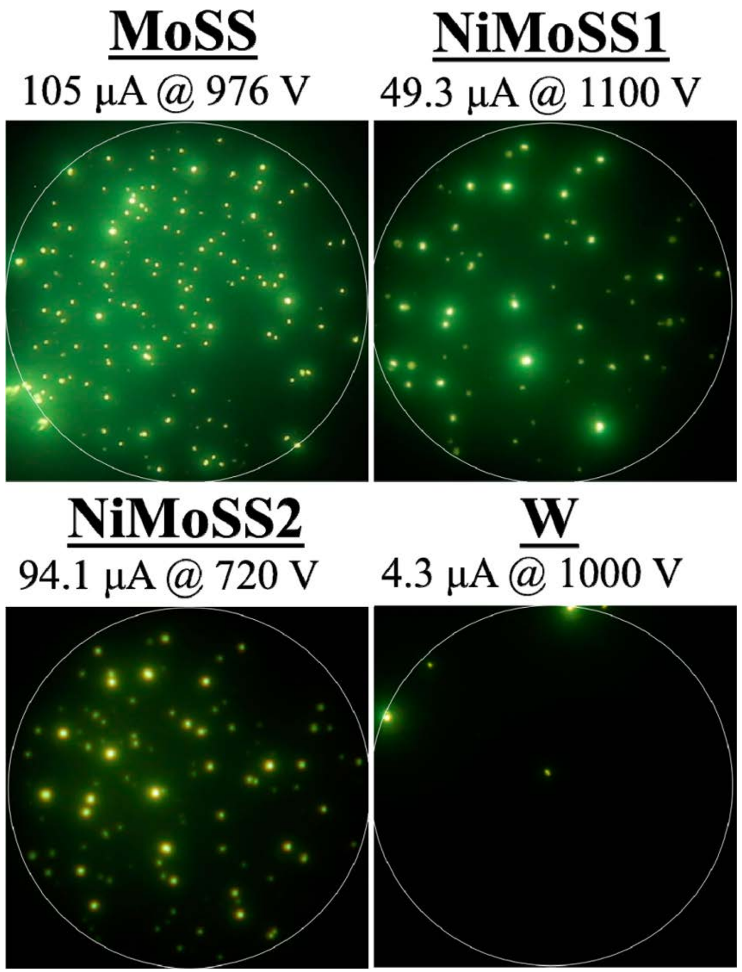


Field emission projection microscope



Baturin and Baryshev, Rev. Sci. Instrum. **88**, 033701 (2017)

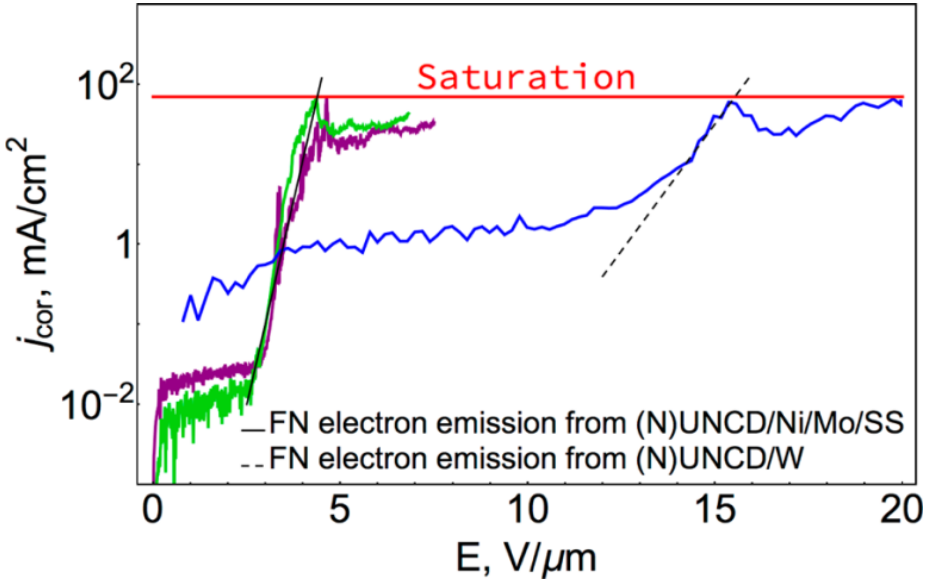
Current density saturation in (N)UNCD



~ In planar uniform (N)UNCD, field emission is not uniform

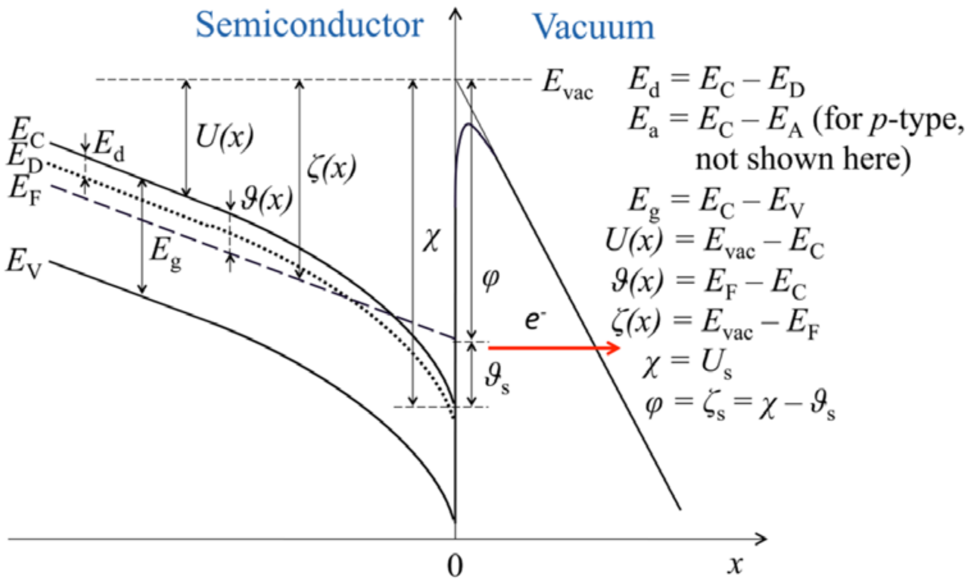
~ Semi-metallic (N)UNCD saturates similarly to semiconductors

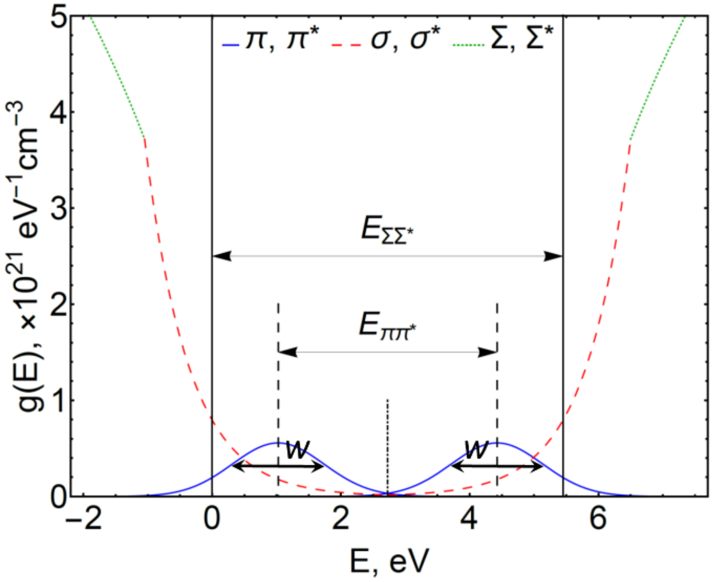
~ Saturation is ~100 mA/cm^2 is specific to (N)UNCD, regardless of substrate

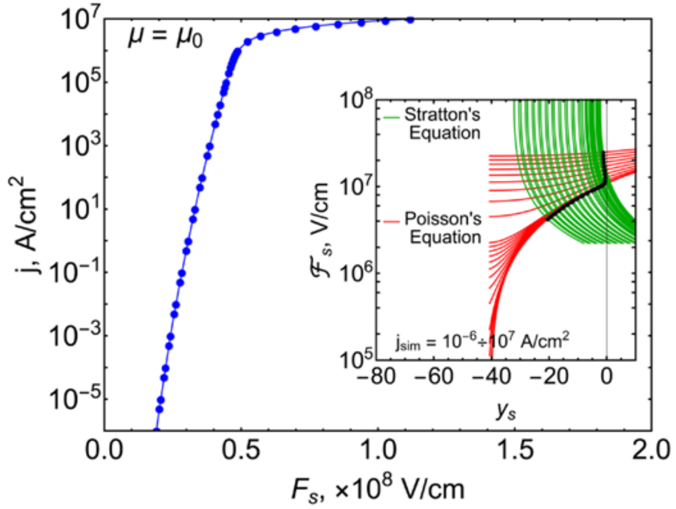


Chubenko *et al.*, ACS Appl. Mater. Interfaces **9**, 33229 (2017)

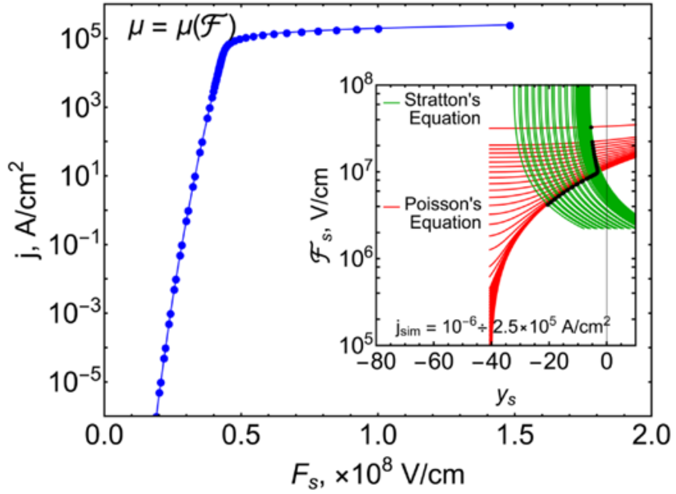
Band structure, SBLF formalism and transport







(a)



(b)

Poisson

$$\frac{d\mathcal{F}}{dy} = -\frac{k_B T/q}{\kappa\varepsilon_0}\frac{\rho(y)}{\mathcal{F} - j/\left\{q[n(y)\mu_e(\mathcal{F}) + p(y)\mu_h(\mathcal{F})]\right\}}$$

Stratton

$$j_{em}^{-}(F_s, y_s) = A_1 \exp\left[-B_1\frac{\chi^{3/2}}{F_s}v(Y_1)\right]\exp(y_s) \times \left[1 - C_1\frac{\chi^{1/2}}{F_s}t(Y_1)k_B T\right]^{-1},$$

$$j_{em}^{+}(F_s, y_s) = \frac{A_2}{t^2(Y_2)}\frac{F_s^2}{\varphi(y_s)}\exp\left[-B_1\frac{\varphi^{3/2}(y_s)}{F_s}v(Y_2)\right] \times \left\{1 - \exp\left[-B_2\frac{\varphi^{1/2}(y_s)}{F_s}y_s t(Y_2)\right] \times \left[1 + B_2\frac{\varphi^{1/2}(y_s)}{F_s}y_s t(Y_2)\right]\right\},$$

Chubenko *et al.*, JAP **125**, 205303 (2019)

Describing saturation: theory vs. experiment

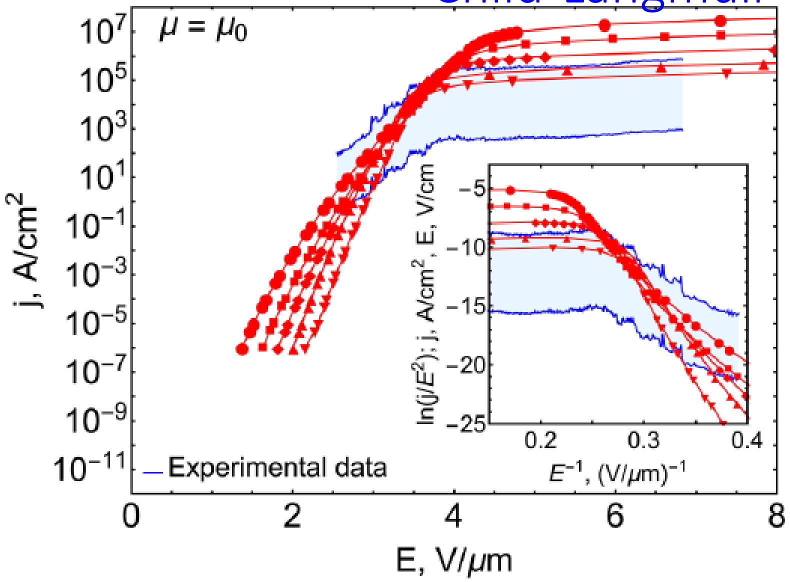
TABLE II. Parameters used to calculate FE characteristics of (N)UNCD films.

Parameter	Value	References
$E_{\Sigma\Sigma^*}$ (eV)	5.45	58
$E_{\pi\pi^*}$ (eV)	2.1	63
w (eV)	0.53	63
E_{m} (eV)	6.5	58
E_0 (eV)	0.68	58
B_1 (cm^{-1})	2.5×10^5	63
B_2 ($\mathrm{cm}^{-1}\,\mathrm{eV}^{-1/2}$)	1.5×10^5	58
μ_0 ($\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$)	1.5	52
$\mathcal{F}_0$ ($\mathrm{V\,cm}^{-1}$)	10^4	
L_{loc} (Å)	10	48
κ	4.5	48
φ, eV	3.6	66

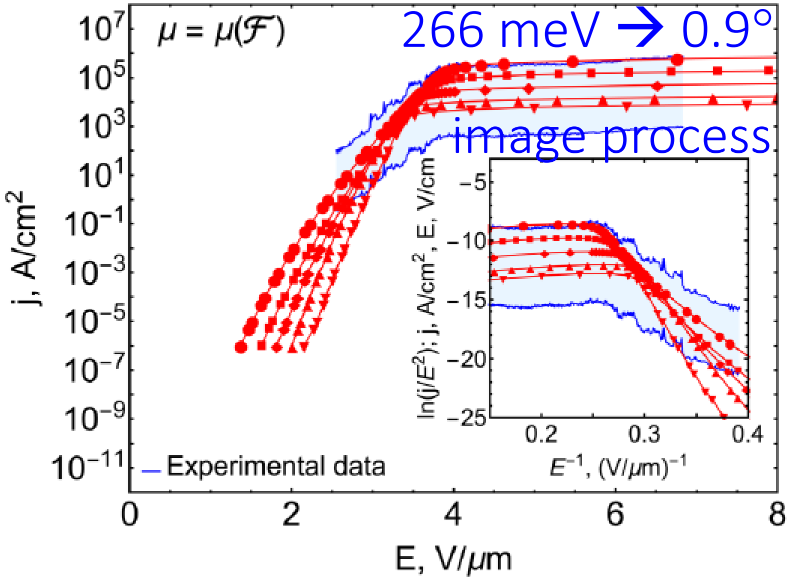
TABLE III. Dependence of electronic and FE characteristics of (N)UNCD on the localization length L_{loc}.

	$L_{\mathrm{loc}} = 5$ Å	$L_{\mathrm{loc}} = 10$ Å	$L_{\mathrm{loc}} = 20$ Å	$L_{\mathrm{loc}} = 40$ Å	$L_{\mathrm{loc}} = 60$ Å
$g(E_{\mathrm{F}})$ ($\mathrm{eV}^{-1}\,\mathrm{cm}^{-3}$)	1.218×10^{20}	4.306×10^{19}	1.522×10^{19}	5.383×10^{18}	2.930×10^{18}
$g(E_{\pi^*})$ ($\mathrm{eV}^{-1}\,\mathrm{cm}^{-3}$)	8.619×10^{20}	3.047×10^{20}	1.077×10^{20}	3.809×10^{19}	2.073×10^{19}
$n(y_{\mathrm{b}})$ (cm^{-3})	4.901×10^{18}	1.733×10^{18}	6.126×10^{17}	2.166×10^{17}	1.179×10^{17}
$n(0)$ (cm^{-3})	1.089×10^{21}	3.849×10^{20}	1.361×10^{20}	4.811×10^{19}	2.619×10^{19}
β	~1850	~1170	~800	~560	~440
$j_{\mathrm{sat}}\vert_{\mu=\mu_0}$ ($\mathrm{A\,cm}^{-2}$)	$\sim 3 \times 10^7$	$\sim 7 \times 10^6$	$\sim 2 \times 10^6$	$\sim 5 \times 10^5$	$\sim 2 \times 10^5$
$j_{\mathrm{sat}}\vert_{\mu=\mu(\mathcal{F})}$ ($\mathrm{A\,cm}^{-2}$)	$\sim 6 \times 10^5$	$\sim 1.8 \times 10^5$	$\sim 5 \times 10^4$	$\sim 1.6 \times 10^4$	$\sim 8 \times 10^3$

$$\mu(\mathcal{F}) = \begin{cases} \mu_0, & \mathcal{F} < \mathcal{F}_0, \\ \mu_0\sqrt{\dfrac{\mathcal{F}_0}{\mathcal{F}}}, & \mathcal{F} > \mathcal{F}_0 \end{cases}$$

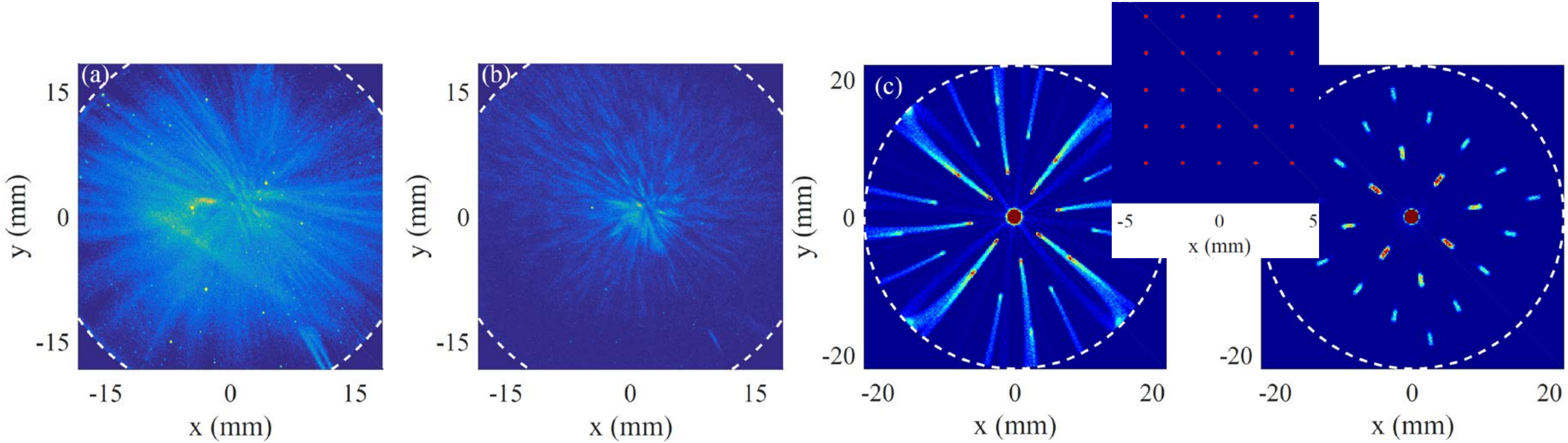


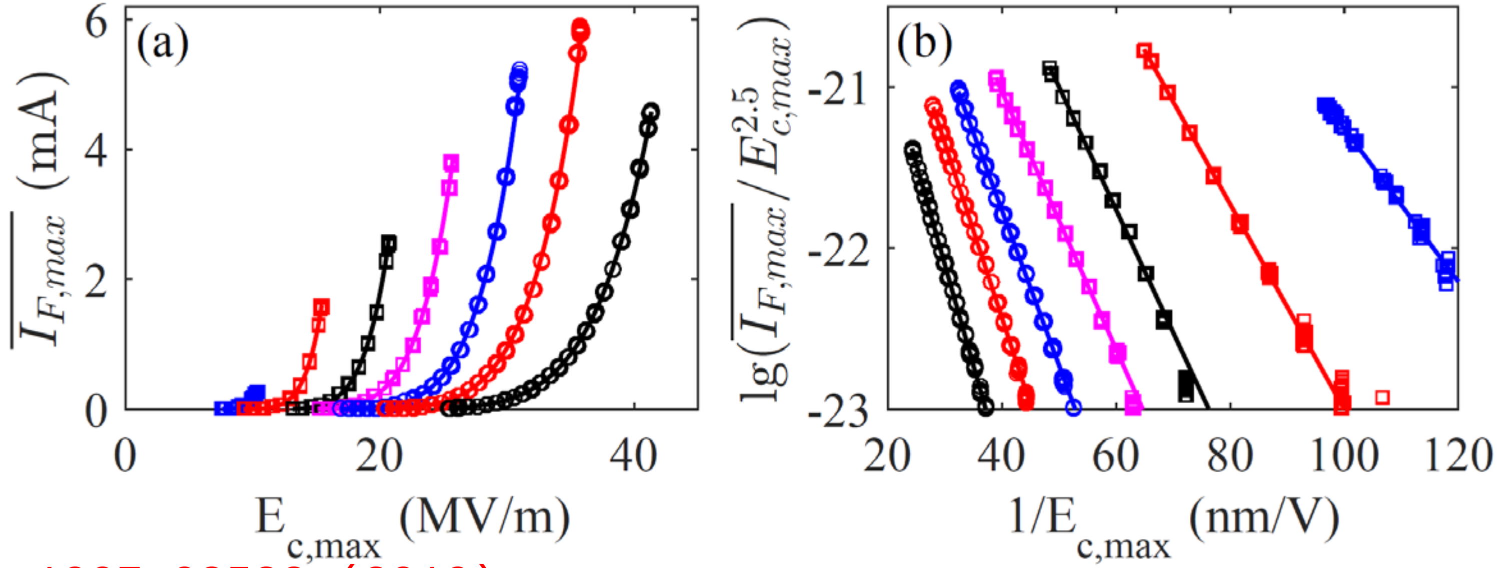
(a)



Chubenko *et al.*, JAP **125**, 205303 (2019)

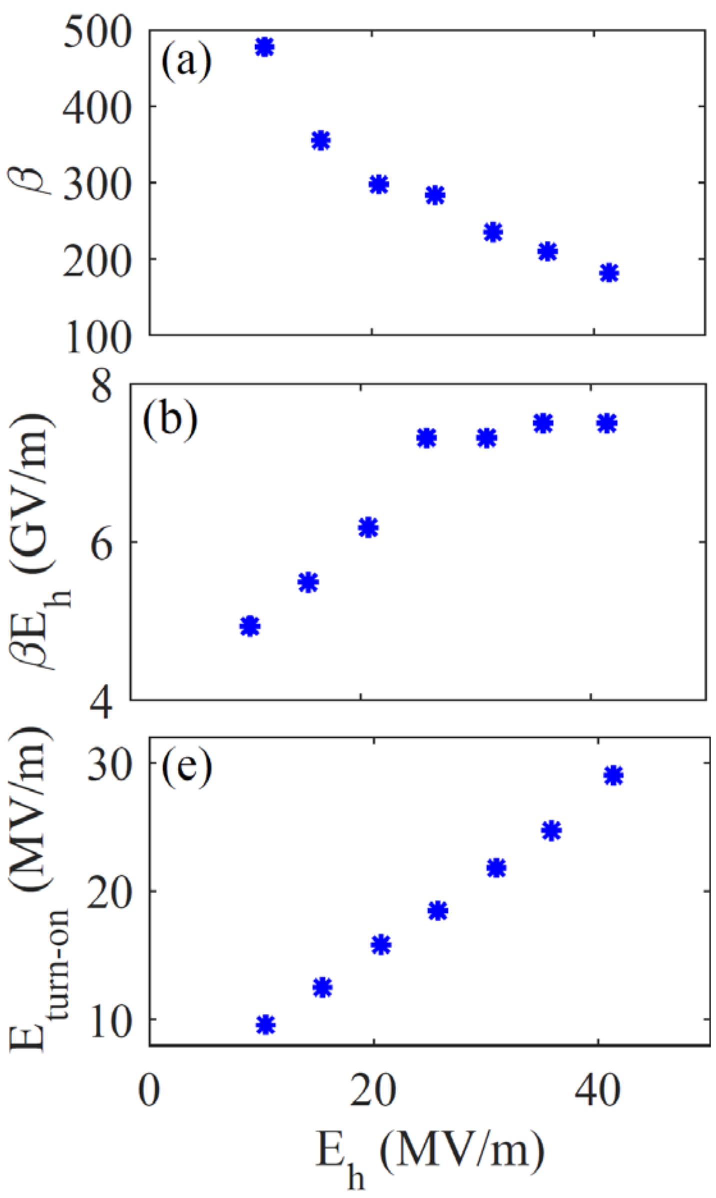
“Conditioning” and imaging at ACT/AWA

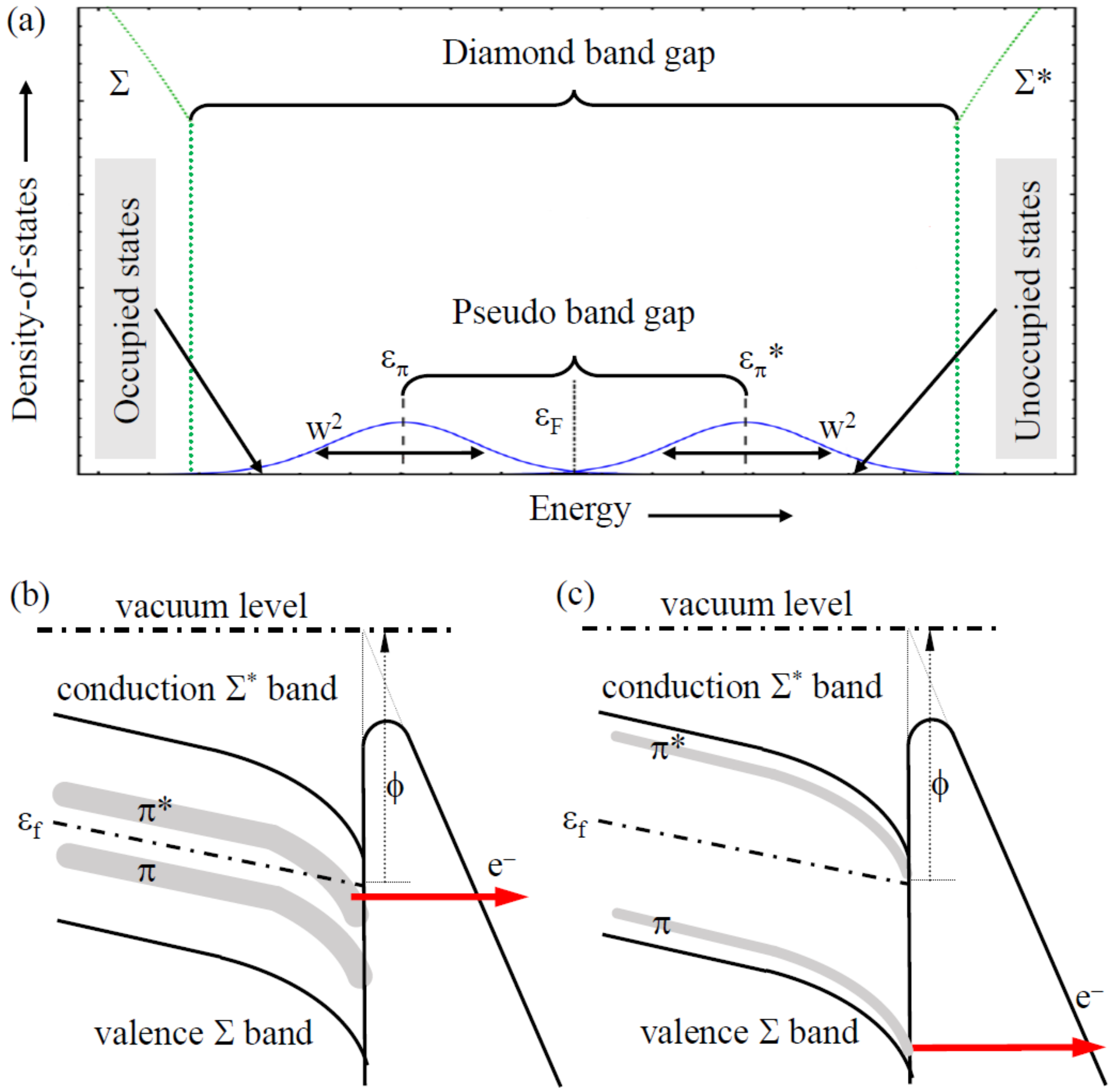




Shao *et al.*, arXiv: 1907.08582 (2019)

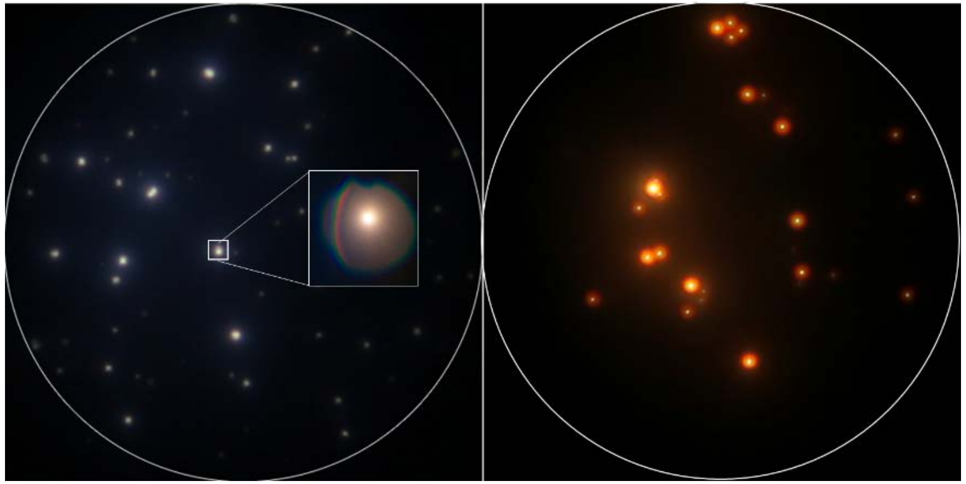
“Conditioning” physics





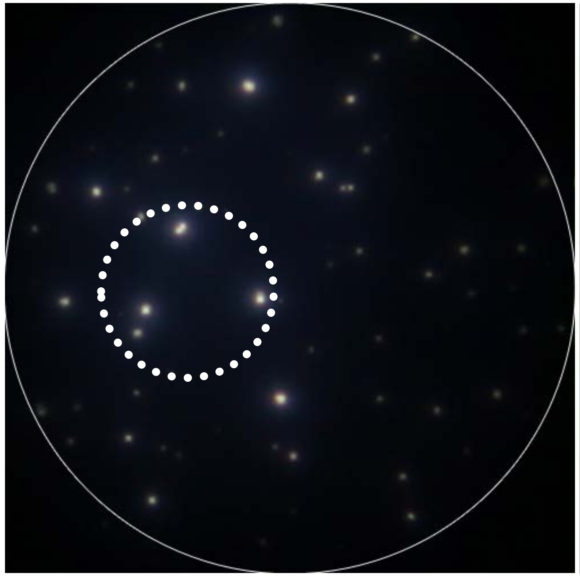
Shao *et al.*, arXiv: 1907.08582 (2019)

Blue light from (N)UNCD

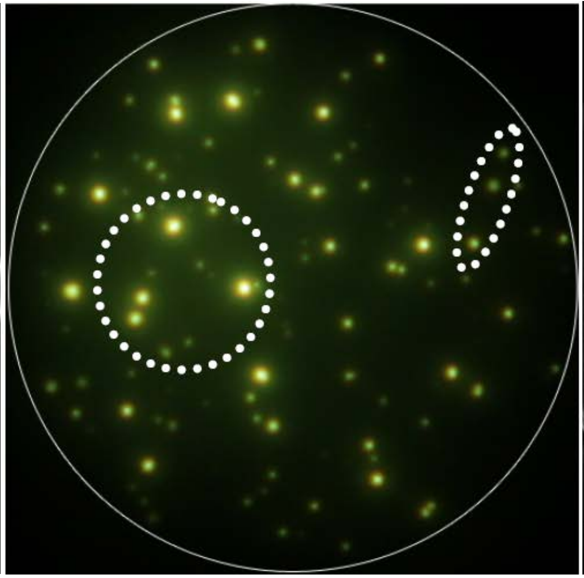


Side-view into the gap

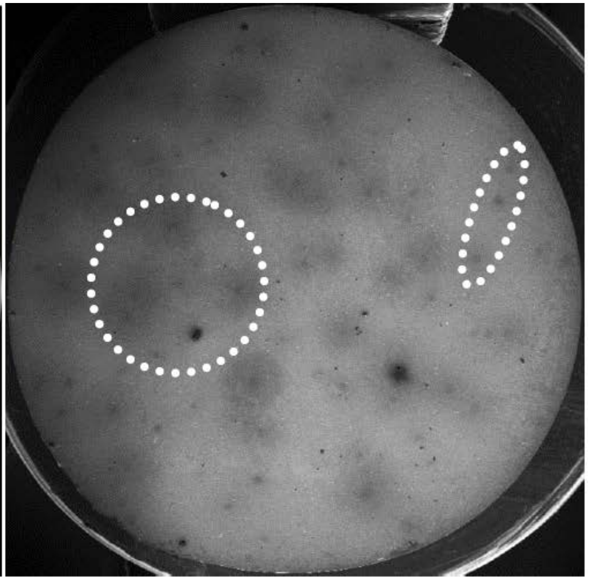
ITO



YAG



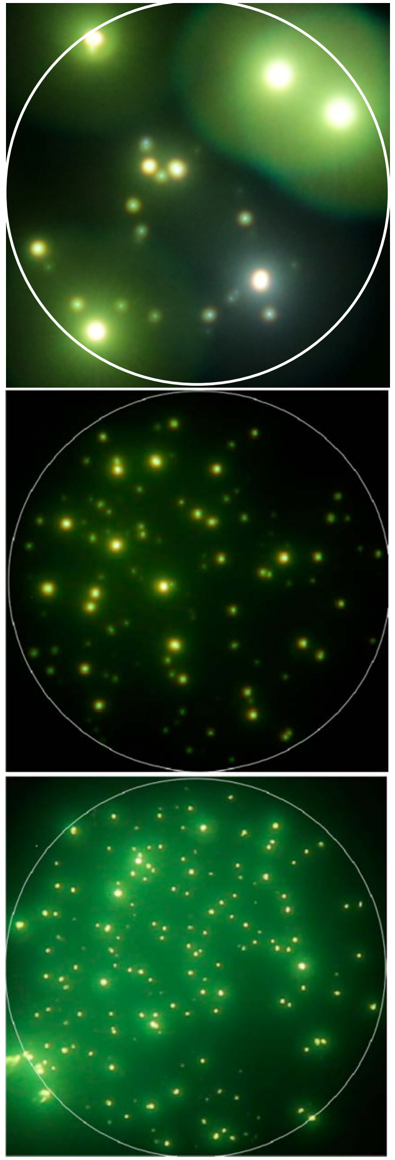
SEM

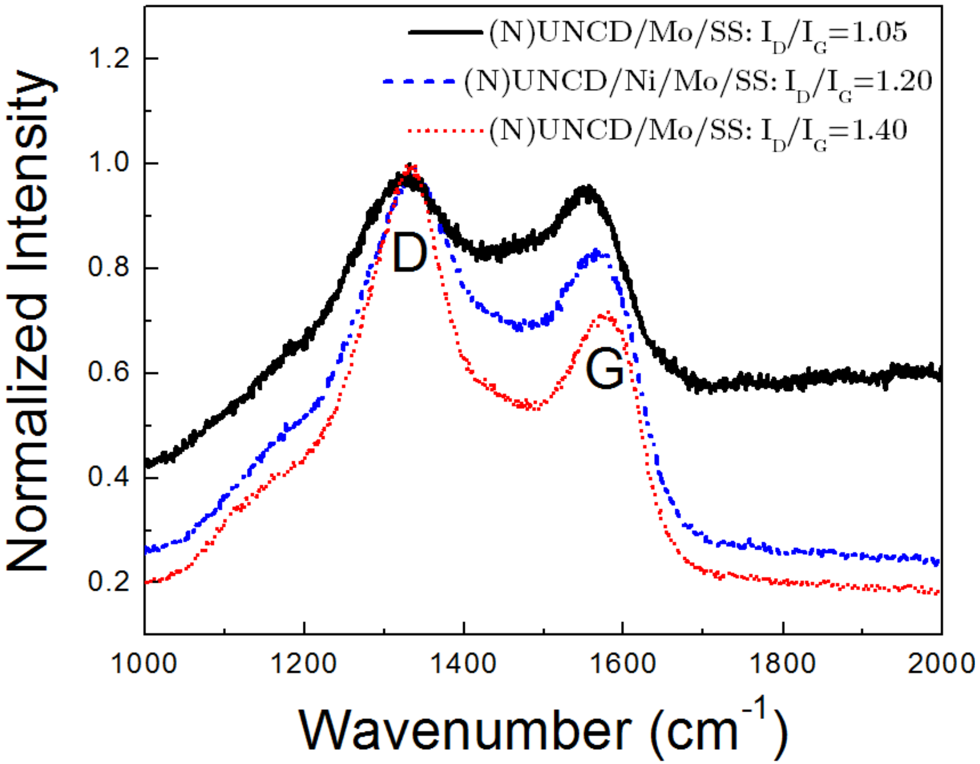


sp^2 content of UNCD versus emissivity

All samples

~100 μA@1 kV



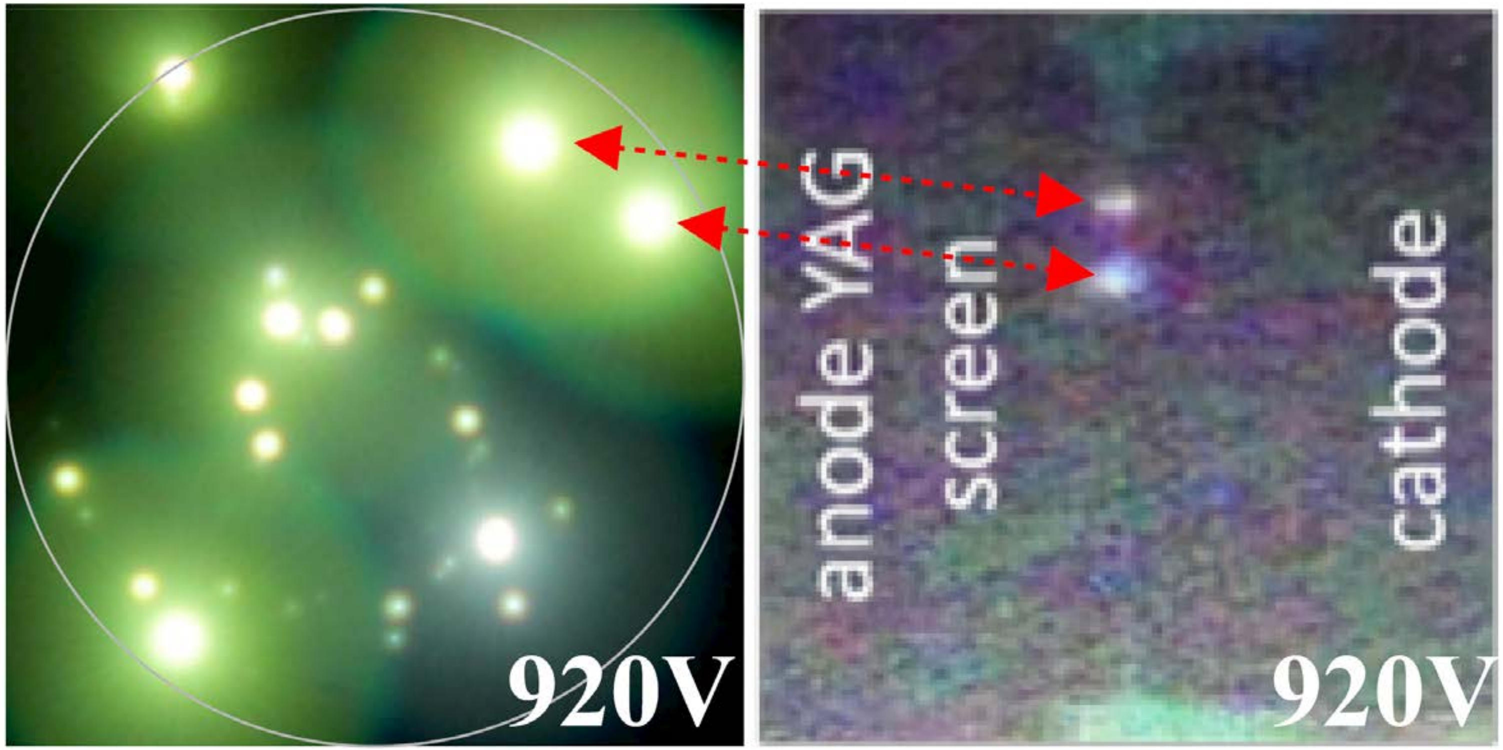


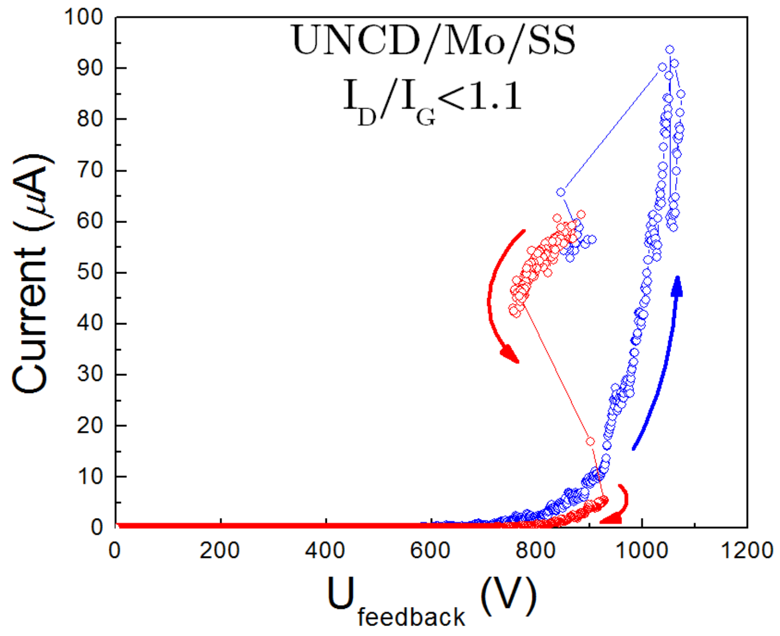
Baturin *et al.*, J. Phys. D: Appl. Phys. **52**, 325301 (2019)

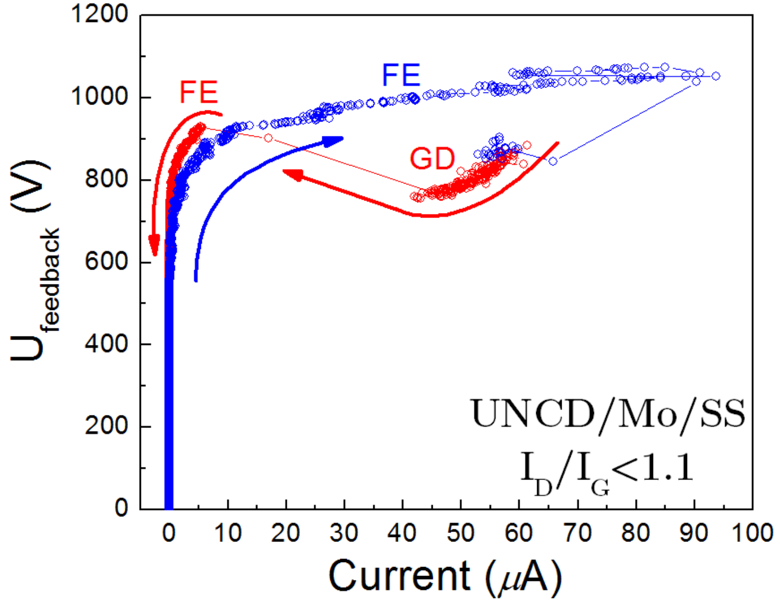
Self-induced, self-stabilized glow discharge

Vacuum ~10^{-9} Torr

Front-view   Side-view



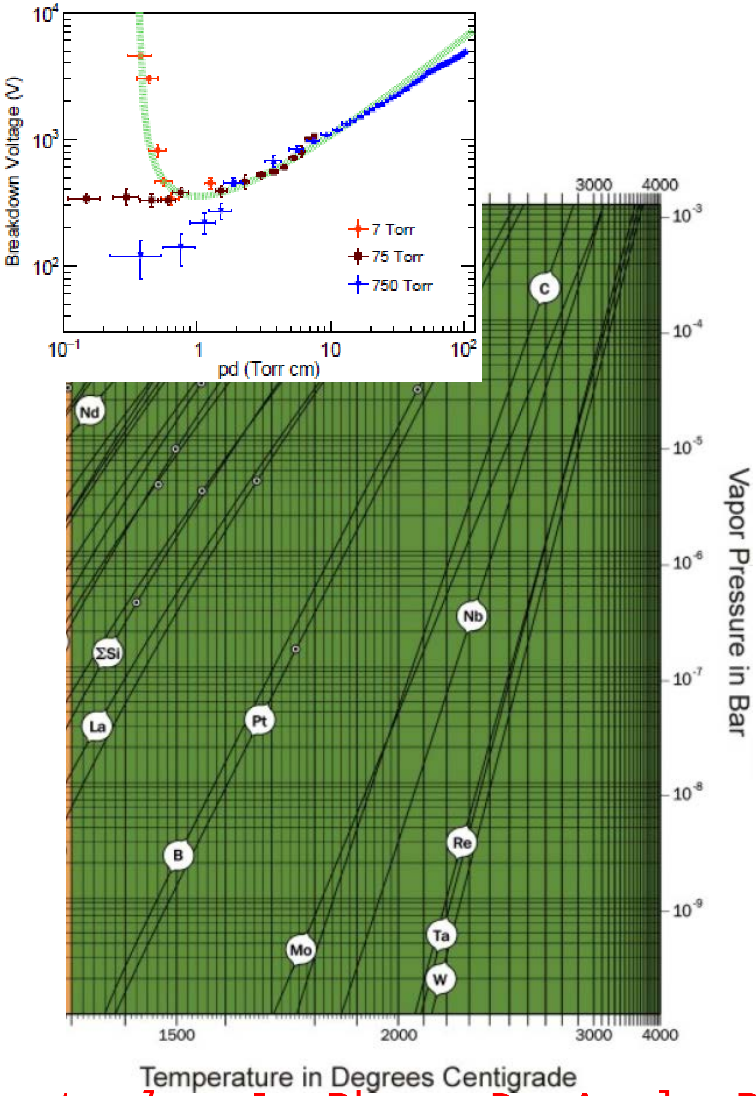




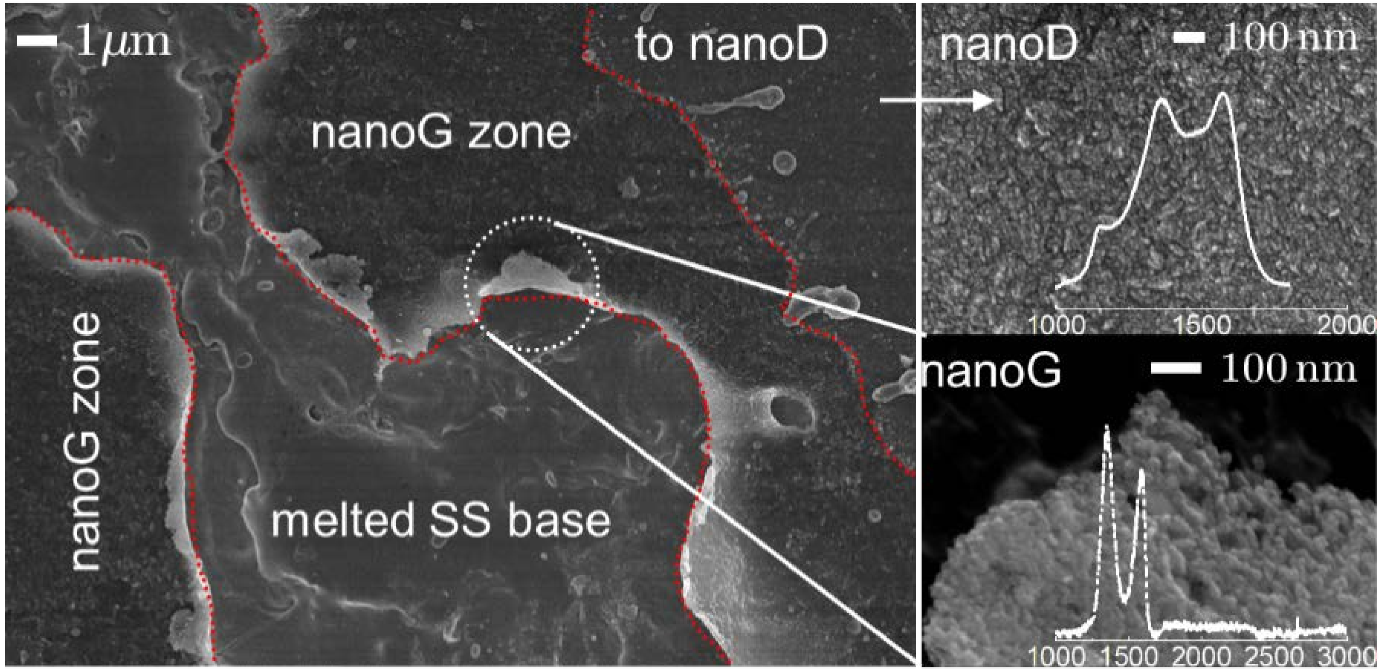
Baturin *et al.*, J. Phys. D: Appl. Phys. **52**, 325301 (2019)

Two estimations on temperature

Phase diagram
(T>~3,500 K)



Diamond-to-graphite
(T>~2,000 K)



Baturin *et al.*, J. Phys. D: Appl. Phys. 52, doi:10.1088/1361-6463/ab2183 (2019)

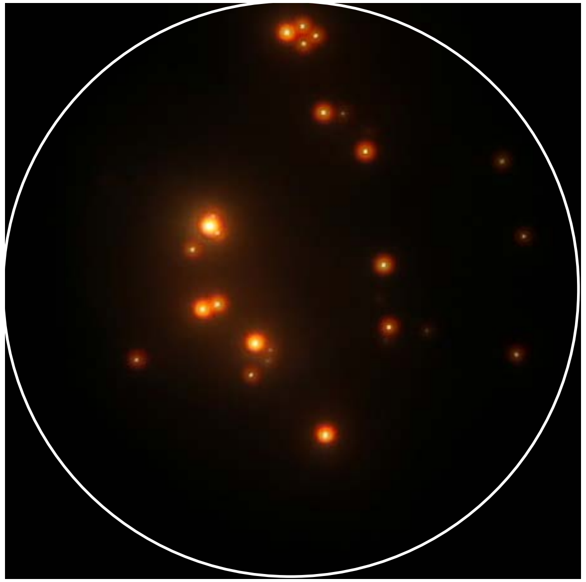
Third temperature estimation

VOLUME 13, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1964

NOTTINGHAM EFFECT IN FIELD AND *T*-*F* EMISSION: HEATING AND COOLING DOMAINS, AND INVERSION TEMPERATURE

F. M. Charbonnier, R. W. Strayer, L. W. Swanson, and E. E. Martin
Field Emission Corporation, McMinnville, Oregon

$$T_i = \frac{d}{2k} = \frac{he}{4k(2m)^{1/2}} \frac{F}{\varphi^{1/2} t(y)} \cong 5.32 \times 10^{-5} \frac{F}{\varphi^{1/2}},$$

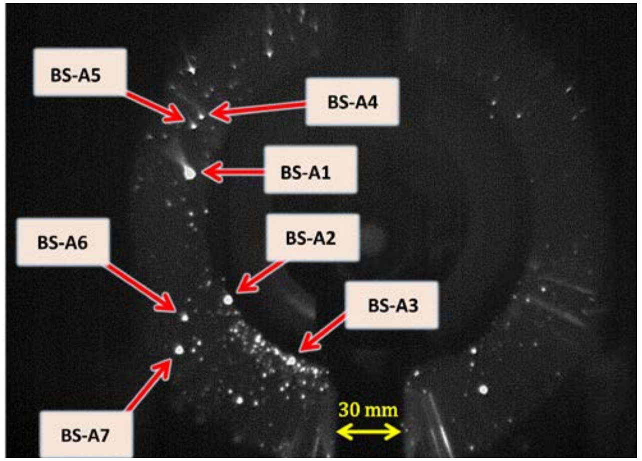


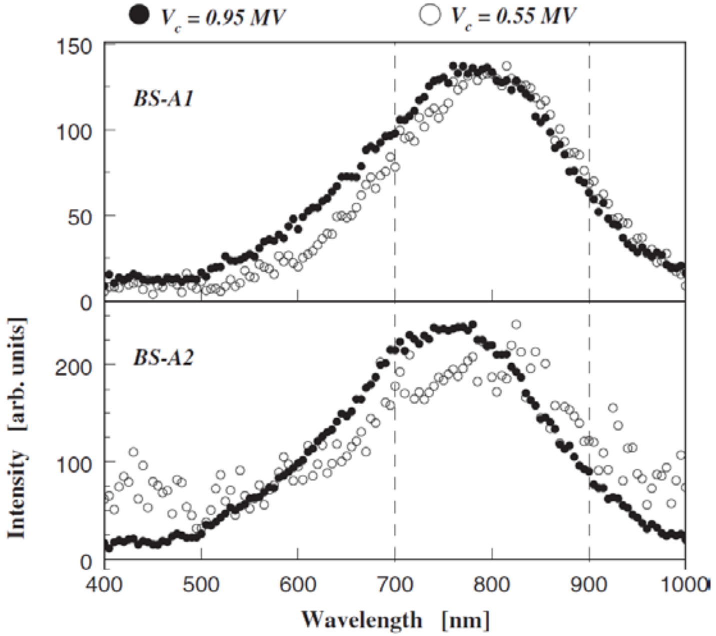
stable 2,000 K
(m_{eff}~1/2m)

unstable 4,500 K
(m_{eff}~1/18m)

KEK/CERN implications: breakdown/arc/discharge

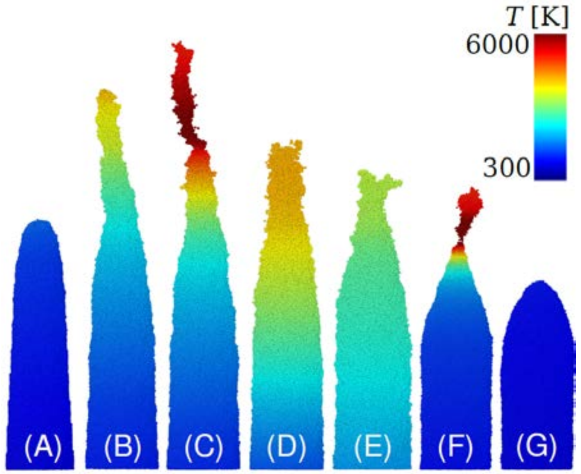
All temperatures at breakdown locations are >1,300 K

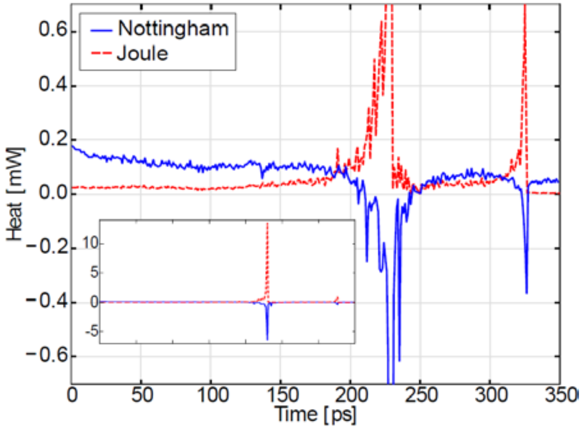


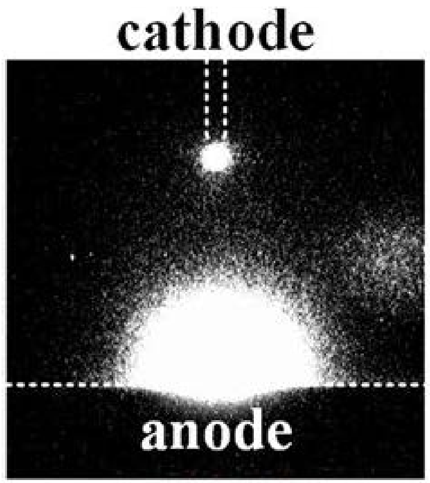


Phys. Rev. Accel. Beams **21**, 122002(2018)

Thermally driven cathodic plasma forms discharge/arc







J. Phys. D: Appl. Phys. **51**, 225203 (2018);
Sci. Rep. **9**, 7814 (2019)