Field Emission Microscopy of Diamond and Nanotube Materials

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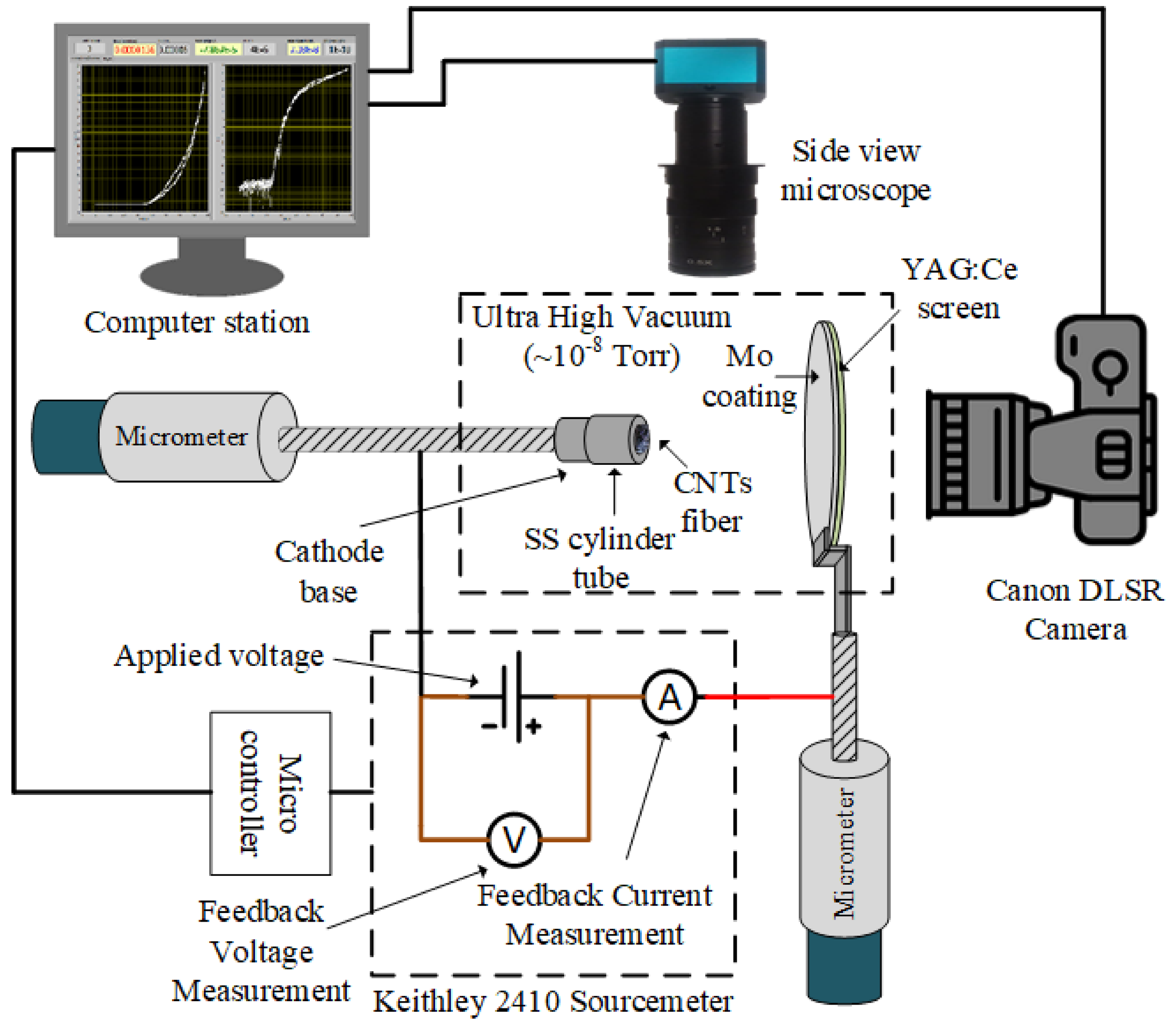
Motivation

1. Quantifying:
   - emission area
   - current density
   - beam brightness

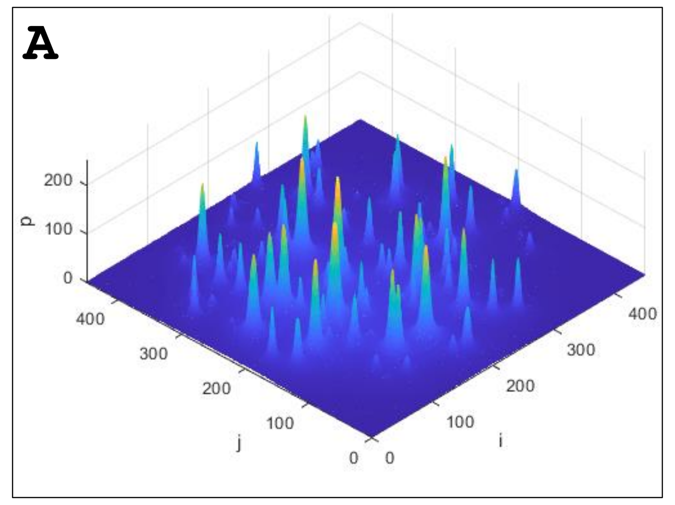
   of field emission cathodes made of carbon nanotubes (CNTs) fiber or ultrananocrystalline diamond (UNCD).
2. Comparing the results with theory.

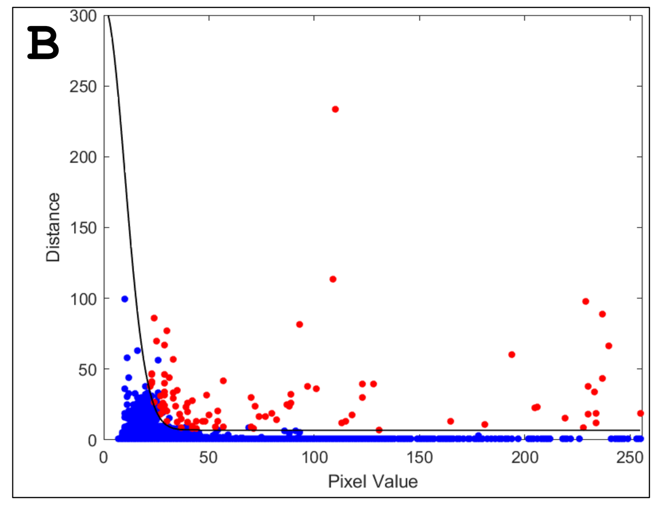
Experiment Setup



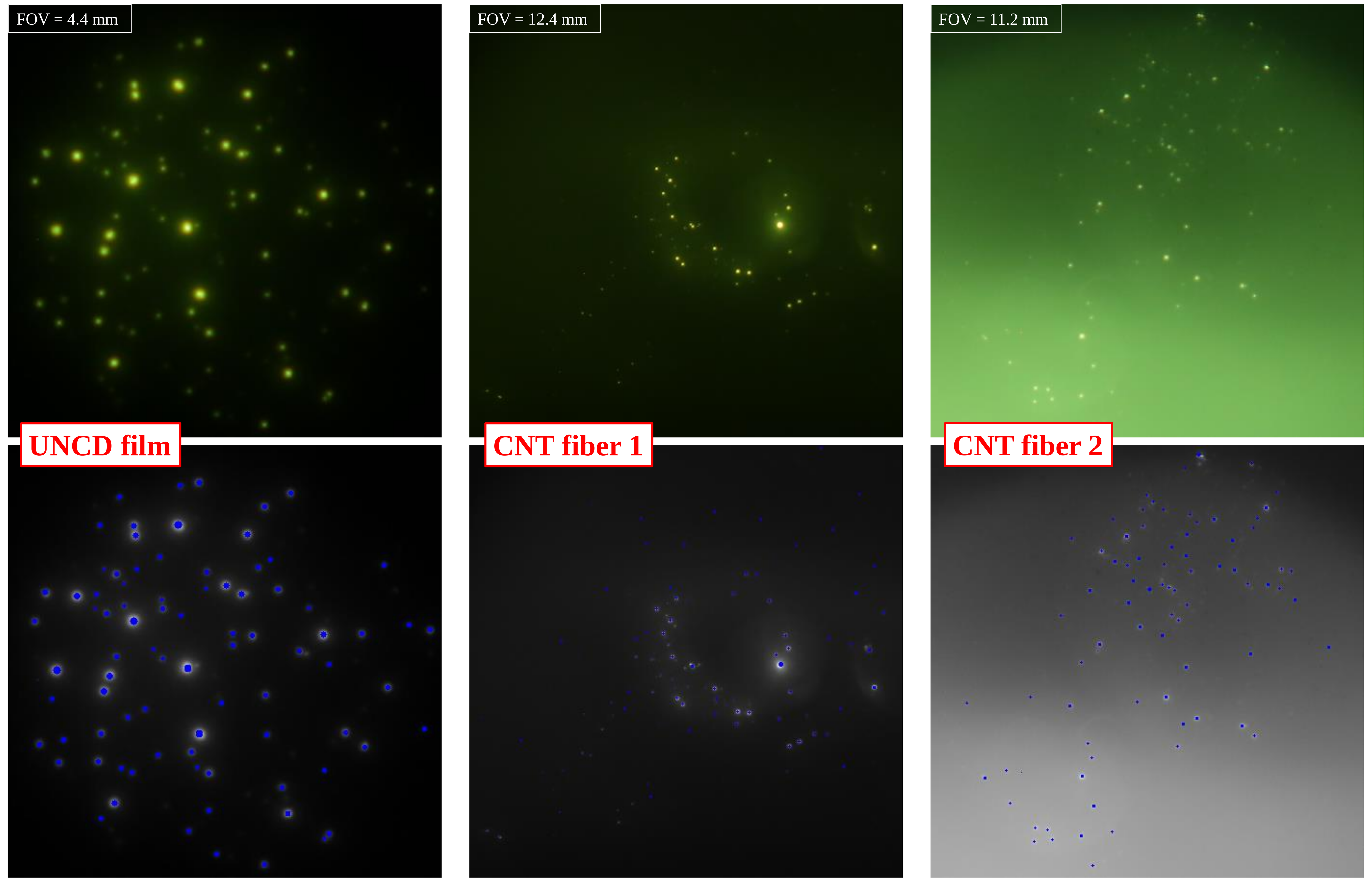
- Anode: Mo coated Ce-doped yttrium aluminum garnet screen (YAG: Ce)
- Cathode: sample under test
- Micrographs are created by capturing the emission pattern on the anode screen by camera.
- Fully automated setup: voltage sweeps, feedback voltage and current is recorded, and photo is taken automatically with regular intervals.

Fast Image Processing



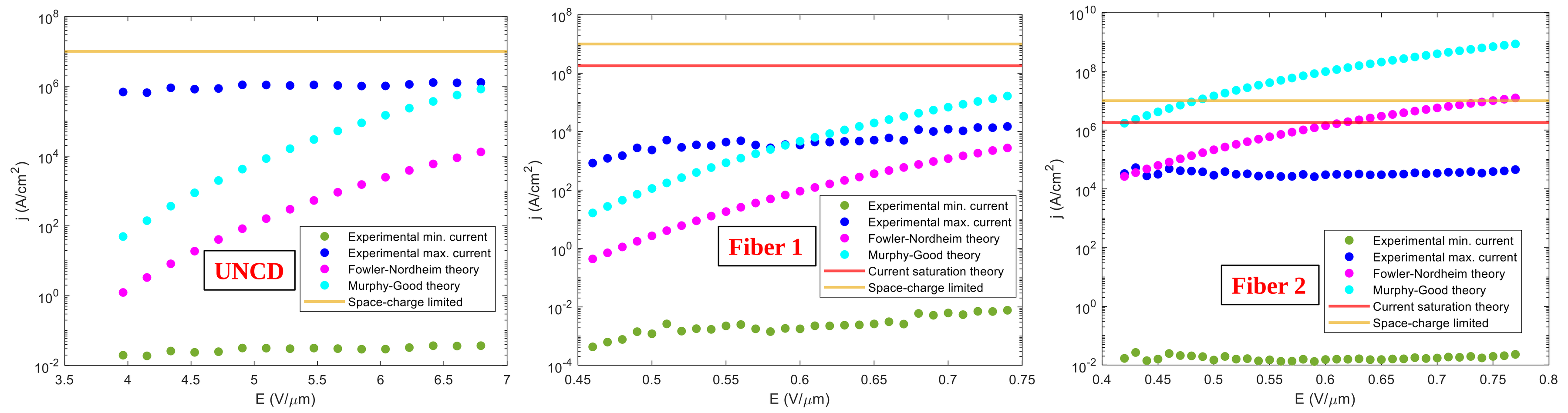


Steps:
1. Each spot appears as Gaussian peaks (Fig.A).
2. Find position of peaks by computing each pixel's distance to nearest brighter pixel and choosing large distance and bright pixels as the peak points (Fig.B).
3. Fitting Gaussian curves to each peak position to filter out false positives and to decide emission area corresponding to the peak.



First row shows typical original micrographs from three sample. Second row shows detected emission area (shown with blue) by the algorithm.

Results and Comparison with theory



Effect of magnification:	$\tan\alpha = \frac{p_x}{p_y} = \sqrt{\frac{2MTE}{m_0c^2}}\frac{1}{v/c}$ $S_{\substack{\text{single domain}\\\text{magnified}}} = \pi(d\tan\alpha)^2$	MTE: mean transverse energy m_0c^2: rest energy v/c: ratio of speed to speed of light d: interelectrode gap α: angle of trajectory
Upper and lower limit of experimental current density:	$j_{\text{exp. min.}} = \frac{I}{S_{\text{appearent}}}$ $j_{\text{exp. max.}} = \frac{I}{\frac{S_{\text{appearent}}}{S_{\substack{\text{single domain}\\\text{magnified}}}} * S_{\text{single domain}}}$	I: measured current $S_{\text{appearent}}$: computed total area of the spots on YAG:Ce $S_{\text{single domain}}$: minimum physical area of an emission domain
Theoretical current density (Fowler-Nordheim and Murphy-Good)	$j_{\text{FN}} = A\frac{1}{\phi}(\beta E)^2\exp\left(-\frac{B\phi^{3/2}}{\beta E}\right)$ $j_{\text{MG}} = A\frac{1}{\phi}(\beta E)^2\exp\left(-\text{v}_{\text{F}}\frac{B\phi^{3/2}}{\beta E}\right)$	ϕ: work function β: filed enhancement factor v_{F}: special elliptic function A, B: constants
Current saturation model of non-metal emitters	$j_{\text{saturation}} = \frac{e\cdot n^{2/3}\cdot v_{\text{saturation}}}{W_{\text{depletion}}}$	e: electron charge n: carrier density $v_{\text{saturation}}$: saturation velocity $W_{\text{depletion}}$: depletion width

Conclusion

- Emission area increases as applied field increases while current density shows saturation in order of magnitude.
- Increase in current is a result of increase in emission area, not a result of increase in current density.
- The trend in current density is different than theoretical prediction of Fowler-Nordheim and Murphy-Good theory.
- Saturation effect cannot be explained with space-charge effect as the current density is much lower than 10^7 A/cm^2
- Discrepancy between theory and experiments can be solved by considering limited charge carriers in non-metal emitters.

References

[1]T.Y. Posos, S.B. Fairchild, J. Park, and S.V. Baryshev, Journal of Vacuum Science & Technology B **38**, 024006 (2020)
[2]T.Y. Posos, O. Chubenko, and S.V. Baryshev, ArXiv:2012.03578 [Physics] (2020)
[3]R.G. Forbes, Review of Scientific Instruments 91, 107101 (2020)