UPDATE 4/99: Massively Parallel Maskless Digital Direct Write E-Beam Lithography

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OUTLINE

- Concept Overview and Capabilities
  - (High throughput and 80 nm feature sizes)
- New System Design (Electrostatic lens concept)
- Material Studies and Field Emission Measurements
  - Promising new materials
- Plans for future development

Massively Parallel Digital E-Beam Lithography Concept

- **The concept is built around parallel electron beamlets from an addressable field emission array (AFEA).**
-

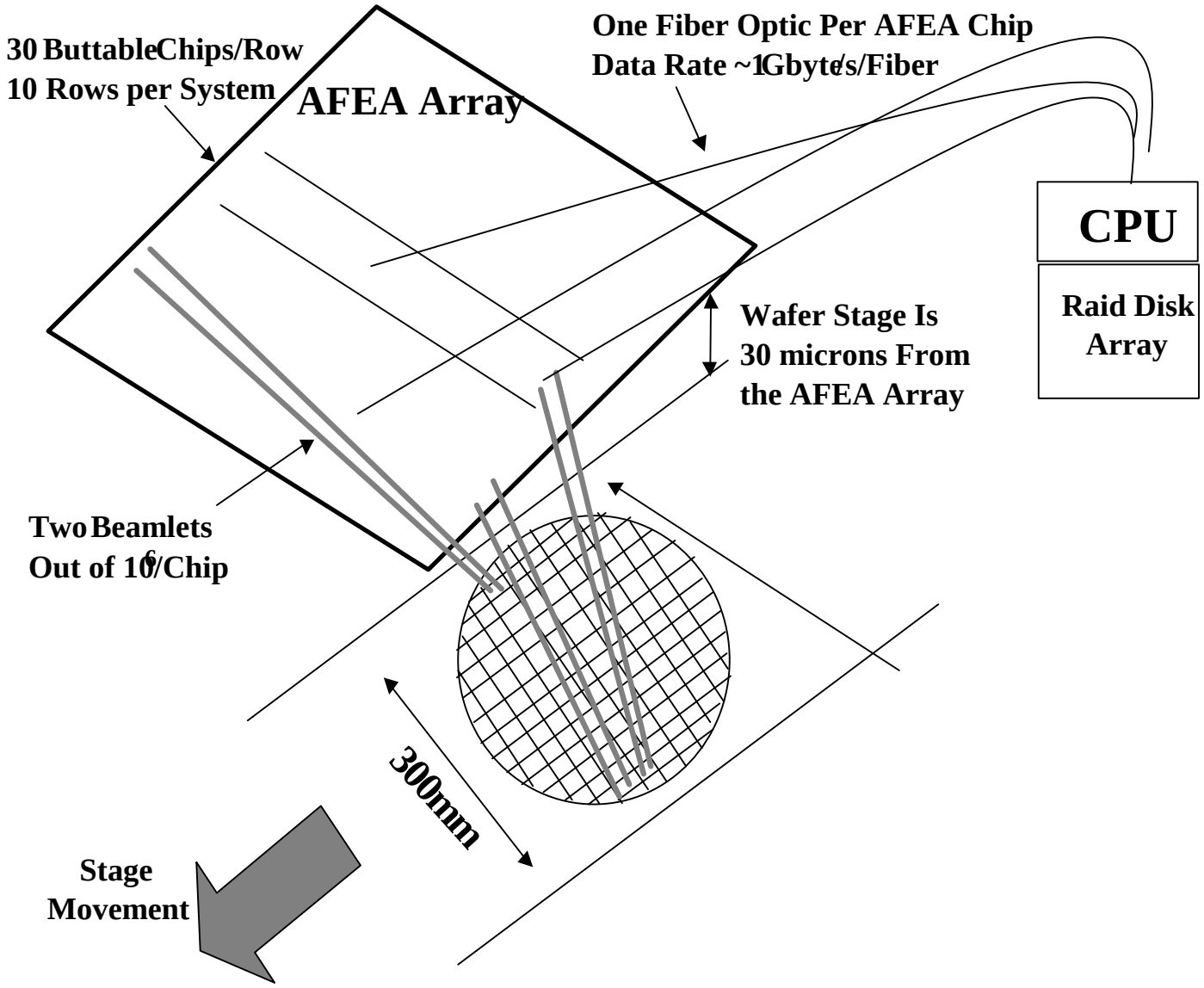
New System Design (1/2)

- Micron-Scale electrostatic lens system incorporated directly on the field emission array chip to focus the 200 nm cathode to a 20 nm pixel (pixel sizes of 10 nm to 40 nm have been studied, corresponding to line-widths from 20-nm to 80-nm)
- No magnetic lens required
- No space-charge limitations
- Working distance from emission array to wafer ~100 μm

New System Design (2/2)

- A 30 cm by 10 cm array of AFEAs could write an entire 300 mm wafer in 30 seconds with 40-nm pixels. This corresponds to writing 6 TeraPixels (TP) per second (firing a 1.8 GigaPixel array at 3.3kHz; average current ~1000 μA at ~200 V, or 200mW power). Write-speed stays constant as pixel-size drops to 10-nm but AFEA emitter density and chip-speed increase.
- The array could be fully redundant--~12 emitters passing over every 20 nm pixel on the wafer, depending on architecture design (distance per move, total number of AFEA chips).
- If absolute reliability was desired, every other emitter could be replaced and the real estate used to drive a detector ring around each cathode--verifying the current delivered by each cathode--a massively parallel low-voltage digital SEM!!

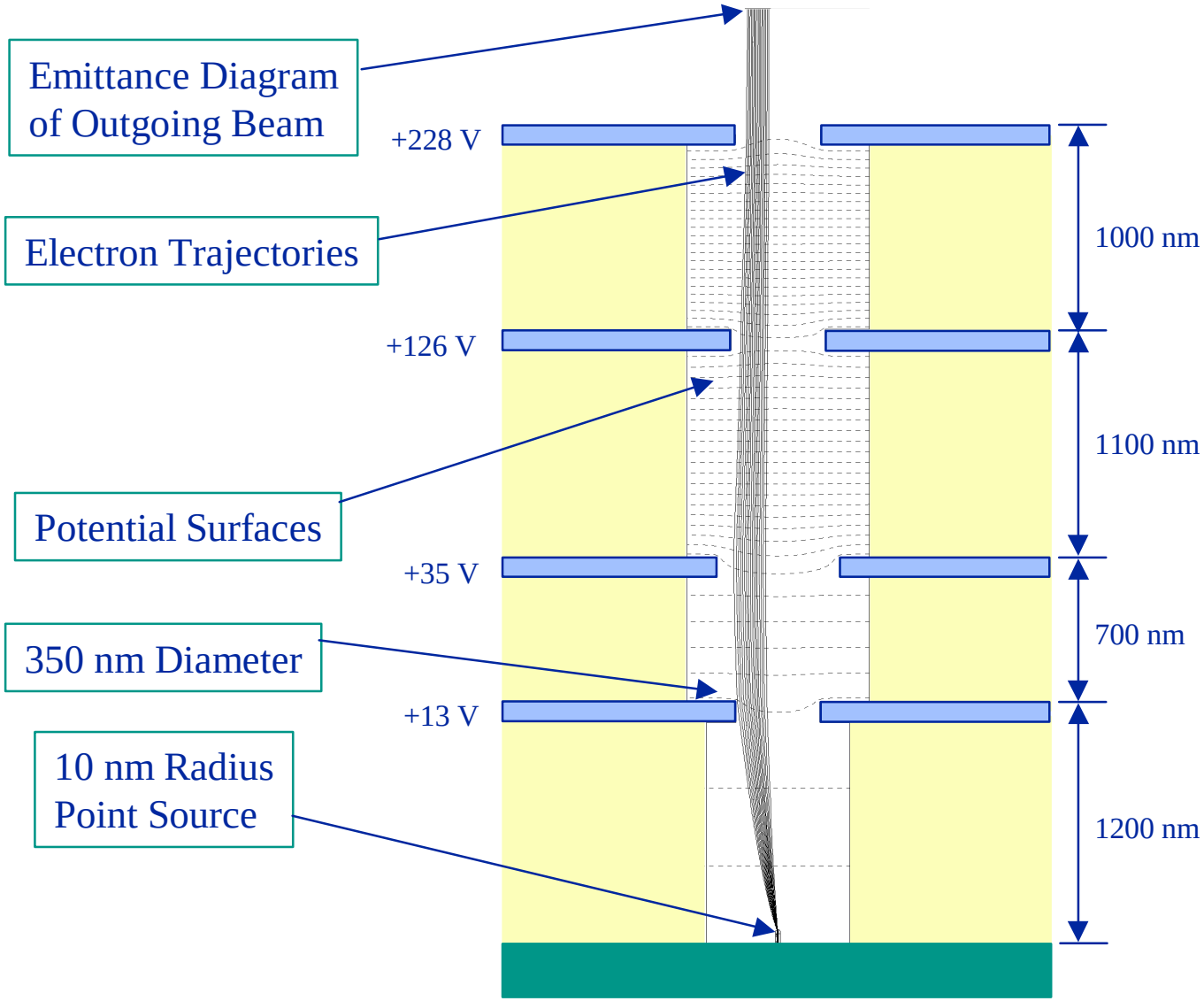
Massively Parallel Electro-Static SEM Array



On-Chip Electrostatic Optics for Electron Beamlet Extraction, Acceleration, and Focusing has been Investigated

- Use conductive grids with nominal 200 nm diameter apertures, or larger
- Up to 4 grids are separated by dielectric insulator (SiO_2)
- Total thickness of all grid structures not to exceed 5000 nm
- Electric field strength limited by dielectric breakdown to 100 V/μm
- Require focused electron beamlet spot size of 40 nm to 10 nm or less at a working distance of 30 - 100 μm
- Write with nominal electron beamlet energy of 200-300 eV, eliminating the proximity effect

Example On-Chip AFEA Electron Beam Emission, Acceleration, and Focusing Optics for a 10 nm Point Source (30-nm spot at 130 mm)



Case RJR1616run17

Crucial Issue

- Stable and reliable electron emitter performance is the key. If a stable reliable solid-state emitter is found, then the system can be built, and will work with very high probability

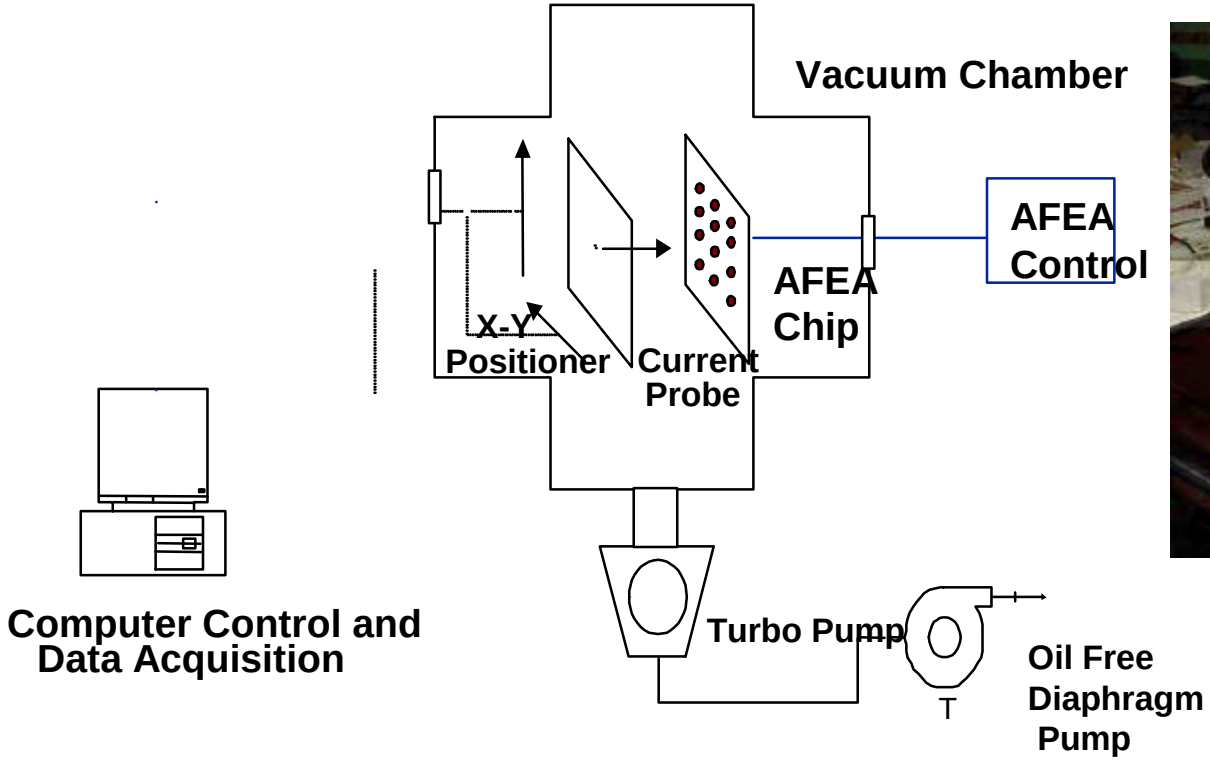
Materials studies (1/2)

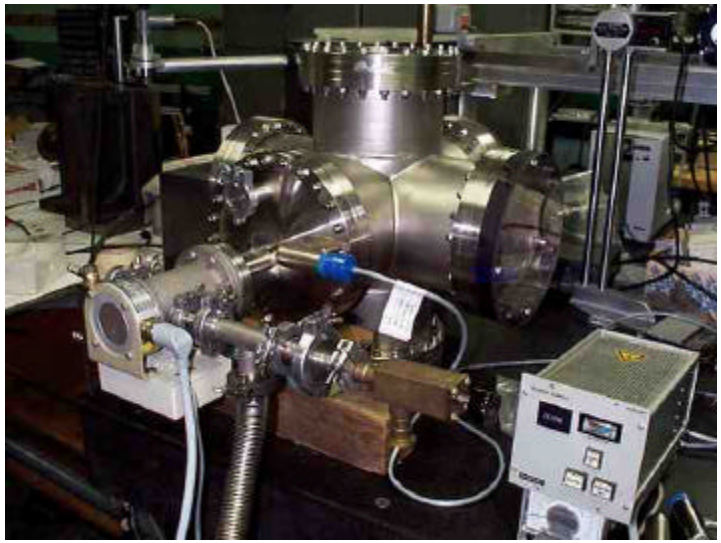
- **Micro-Probe Testing System Operational in 3/98**
  - » Flat Plate method of emission measurement can be very misleading-- may document the properties of a single emission site over an area of mm^2
  - » Emission measured with the micro-probe are characteristic of micron-sized materials samples
- **Materials Testing Studies:**
  - » Varying Concentrations of Sp3 (diamond) bonding in the a-D (amorphous diamond) film (30% to 90% Sp3 bonded)
  - » Varying thickness of the a-D film
  - » Doping of a-D film
    - – **Nitrogen (done)**
    - – **Na (K??) (material acquired for PLD, planned)**
    - – **Cs (materials and equipment ready, planned)**

Materials studies (2/2)

- **Adding nano-structure**
  - **Nano-soot** covered by a-D (done) (High emission threshold)
  - **MgO cubes** (~2 nm) covered by a-D (done) (High emission threshold)
  - **Micro-Columns** (MC) covered by a-D (done) (Structure too large)
  - **Bucky-balls** (C60) with a-D (done) (High emission threshold)
  - **Ion milling** of a-D (vary Sp3 --done) (High emission threshold)
  - **Diamond nano-chips** (done 9/19/98) (Moderate emission threshold)
  - **HF-CVD-carbon** (done/in-progress) (Low emission threshold and stable)
  - **Silicon nano-pillars** with a-D, doped a-D, ND (planned)
  - **Carbon nano-tubes**, deterministically grown --extremely promising!! (experiments under construction)
  - H_2 (~10^-5 torr) atmosphere lifetime extension (in-progress)

Testing of AFEA Chip Electron Emission in Vacuum

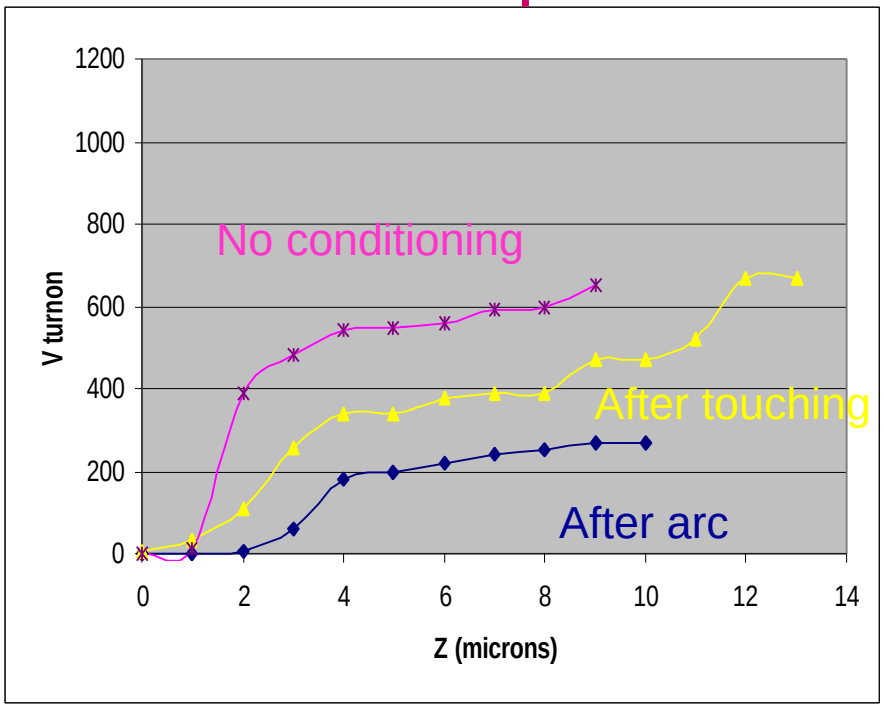




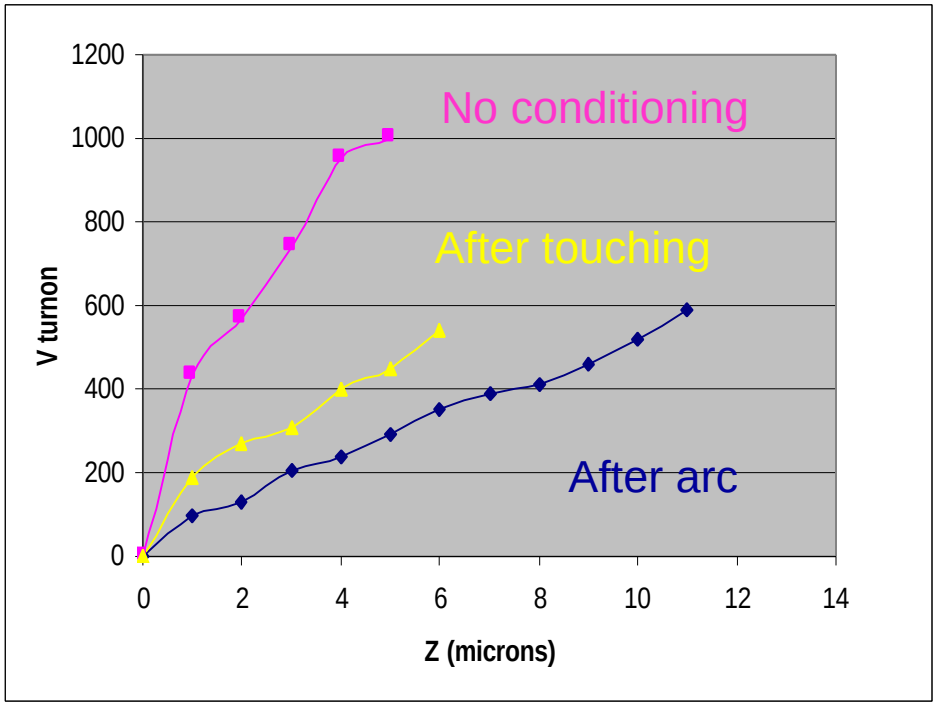
- Schematic of AFEA electron emission test facility for micron-scale probe measurement of current uniformity and stability in a high vacuum environment.

Field emission is much stronger with sp3 a-D coating on MC

MC with sp3 a-D



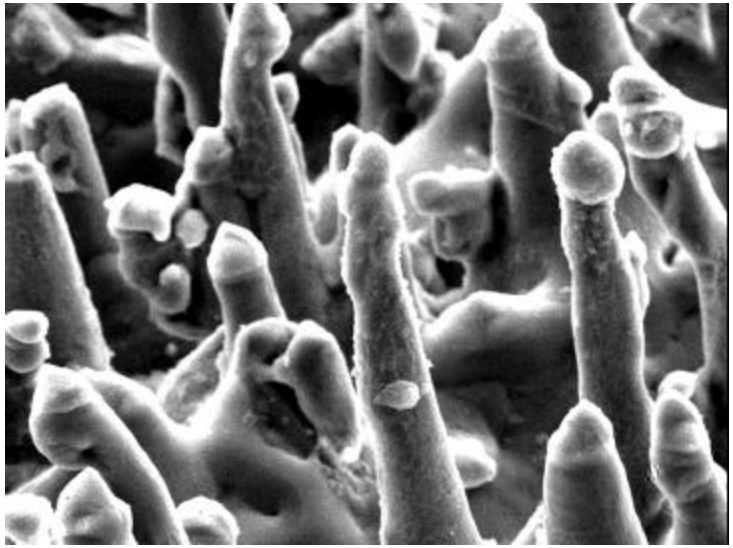
MC with no a-D

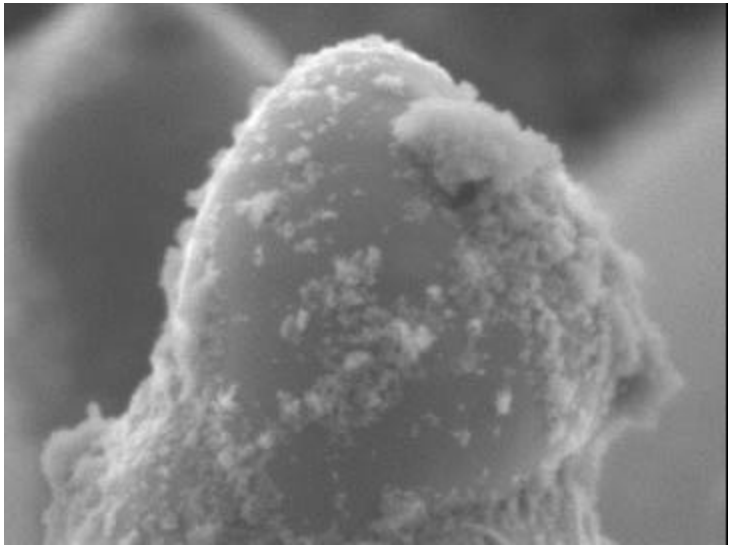


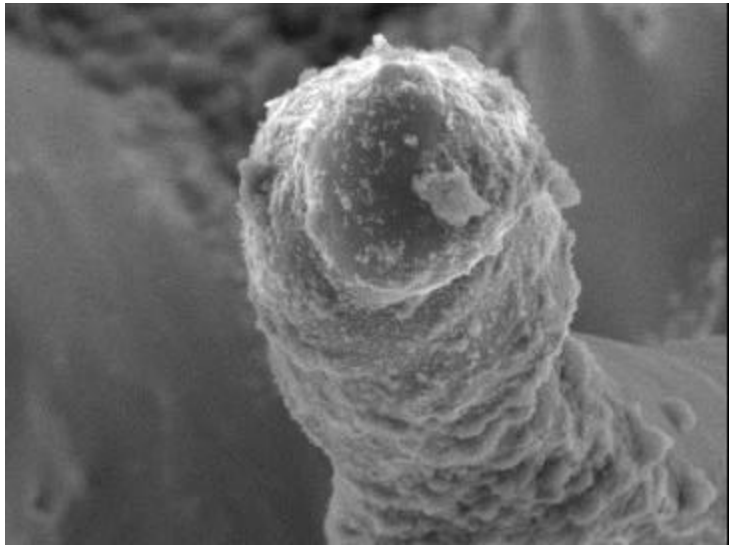
- Data from the micro-column (MC) sample with sp3 coating shows significantly lower field emission threshold. (10V/µm slope)
- Both samples show improved emission with arcing or touching the surface with the probe tip.

Immature Array of Si Micro-columns (MC) Coated with Nanocrystalline Diamond (diamond nano-chips)

- Nanocrystalline diamond (ND) coating
  - » ND size: ~ 1 – 10 nm
- Entire process: Room temp, in air
- FE threshold after conditioning (for I = 1 nA)
  - » Best ~ 11 V / µm
  - » Typical ~ 15-16 V / µm
- Further enhancement of emission should result from sharpening tips







Diamond Nanocrystal (ND) Plans

- Emission from the Micro-Columns (MC) without ND is not dramatic--improvement with the ND or a-D is dramatic
- **Understand stability and reliability**
  - » Long-term testing may also require modifications to the micro-probe system to measure and adjust for probe drift (the probe is fine for 30 minutes or so, but can be expected to have micron-scale drifts over longer periods)
- **Future topics**
  - » Nano-diamond or a-D/doped a-D on silicon nano-pillars
  - » Emission from ND chips on flat metal/silicon

Silicon Nanopillars can be deterministically grown in 10 nm size

- T. Tada and T. Kanayama, Vac. Sci. Technol. B, 16(6 1998, pp. 3934-3937
- Varying the metal catalyst varies the pillar size

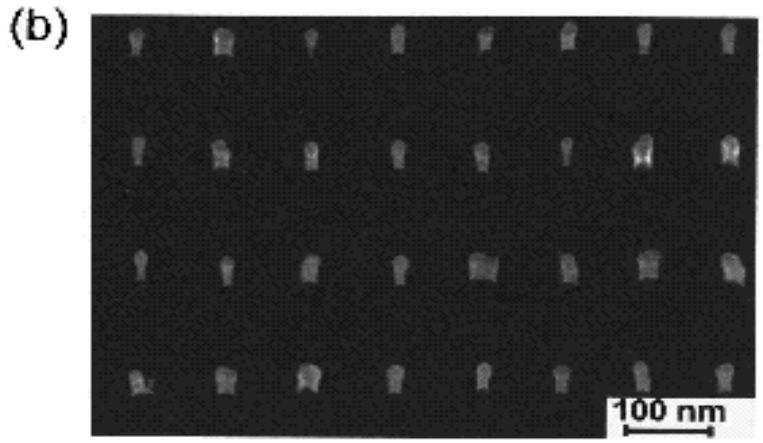
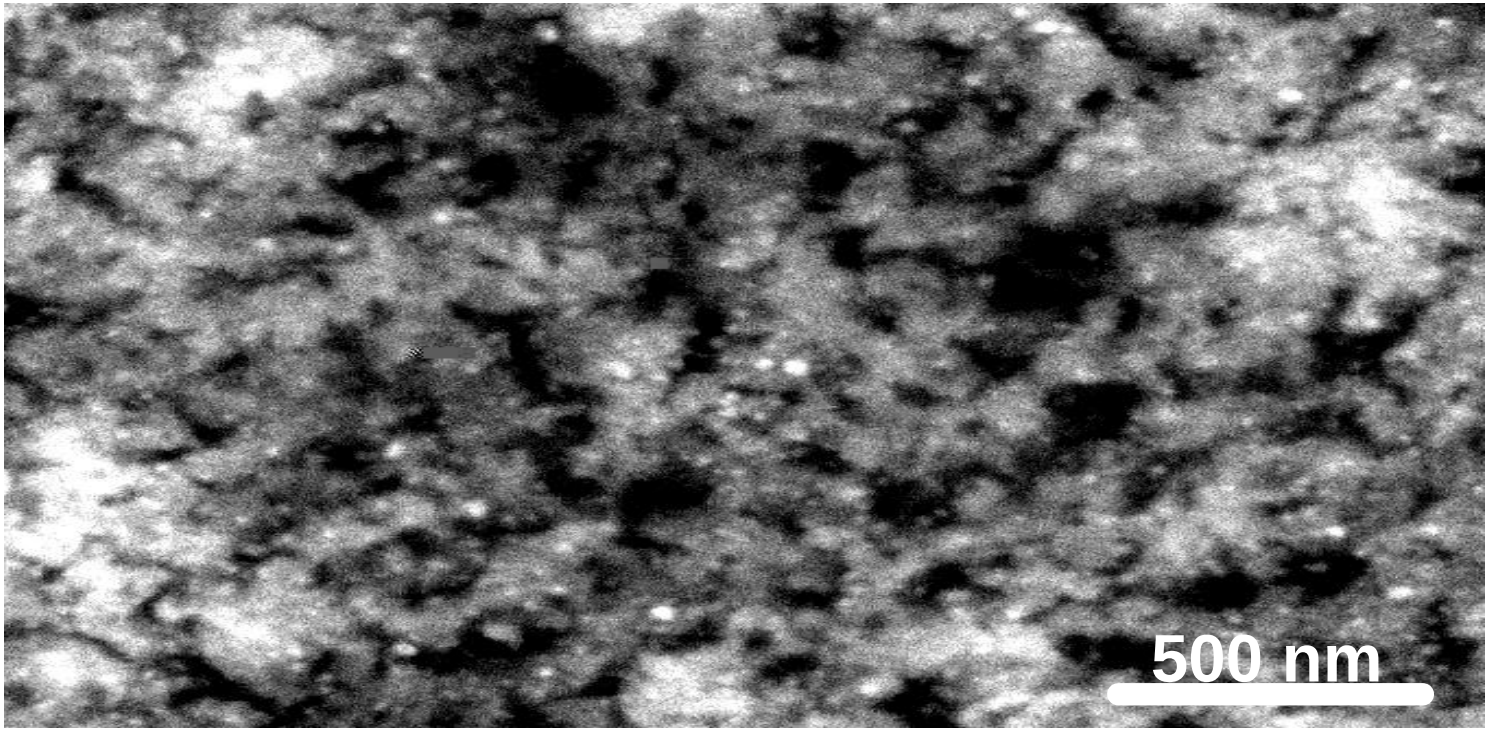


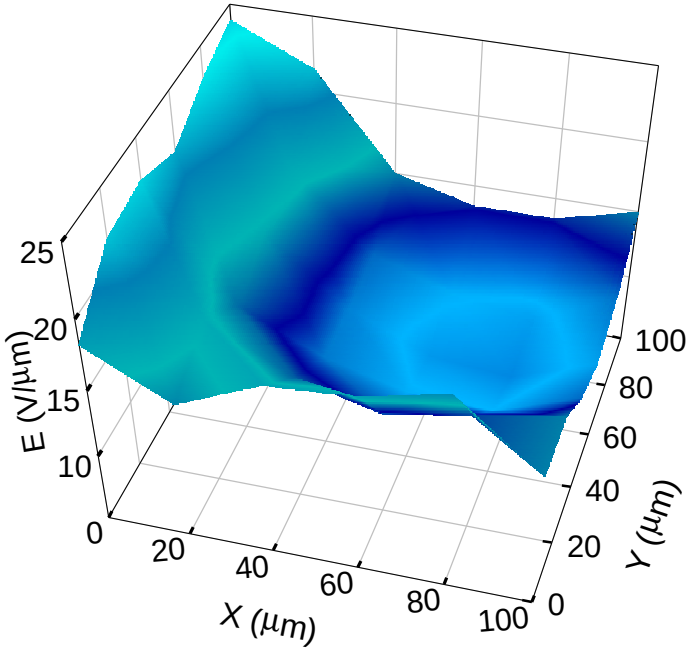
FIG. 3. SEM images of regular arrays of (a) Ag clusters and (b) the resulting Si pillars. The tilt angles for the SEM observation are (a) 0° and (b) 40°.

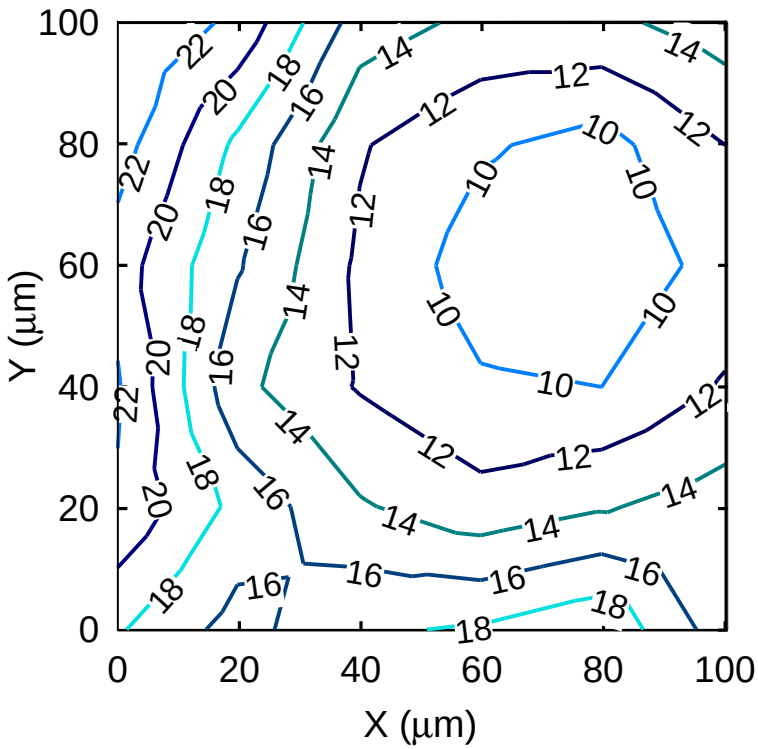
Recent results with HF-CVD carbon are encouraging



- Nanostructured, low-E_{th} a-C film deposited by Hot Filament-CVD. (ORNL SSD)
- A high-resolution field emission SEM (FE-SEM) image which reveals pronounced nanoscale structure in this film that is presumably correlated with its low-E_{th} emission

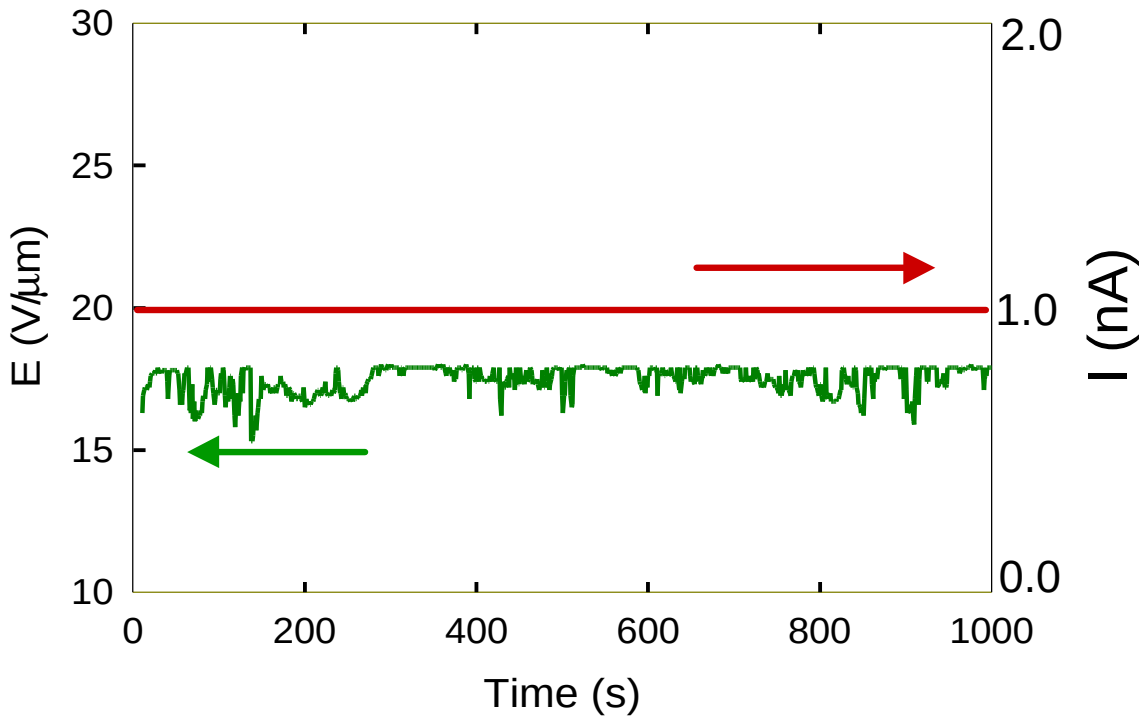
Emission is uniform over wide area for HF-CVD a-C





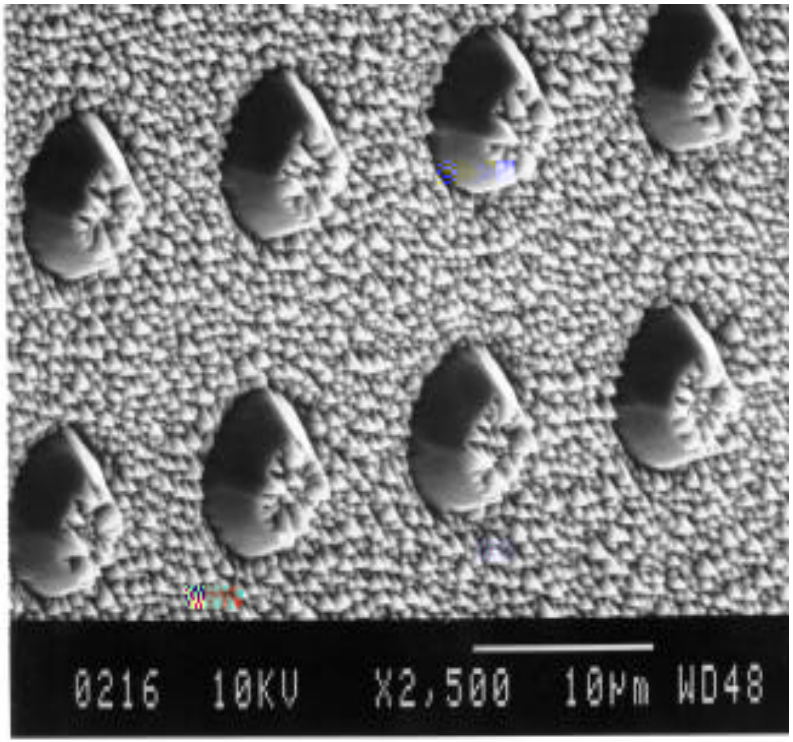
- Results from turn-on testing for a HF CVD a-C sample over a 100x100 μm area. Electric field required to extract 1nA is plotted for the 2D region tested. Measurements made with 25 μm probe at 20 μm distance from sample.

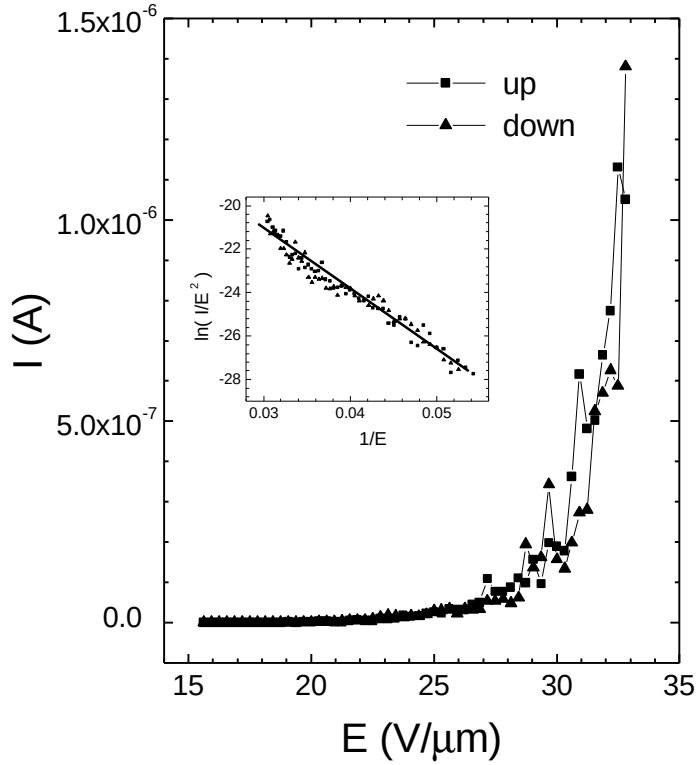
Electron Emission from HF CVD a-C is Stable



- Results from stability testing for a HF CVD a-C sample using a Keithley 237 source-measure instrument operating in current source mode. Measurements are made with 25 micron probe at 10-35 micron distance from sample. Continuous operation for 16 hours has been observed along with cumulative operation of 52 hours at one site.

Etched Si Substrate with HF-CVD Enhances Emission by 50%





- A metal catalyst is used to grow pyramid structures after plasma etch.
- The electron emission from the HF-CVD shows Fowler-Nordheim characteristics. Fluctuation may be due to multiple emission sites.

Carbon Nanotubes can also be deterministically grown by lithography of metal catalysts

- Huang, Zu, Ren, et al., Appl. Phys. Lett., V. 73, No. 26, 28 Dec., 1998, pp. 3845-3847 (SUNY, Buffalo)
- Z. Ren recently reported 10 nm vertically grown carbon nanotubes using Cobalt catalyst and low-temperature CVD (unheated wafer)
- One author reports drawing low voltage current from nanotube until explosion (his probe, not the nanotube!), MRS, Fall '98

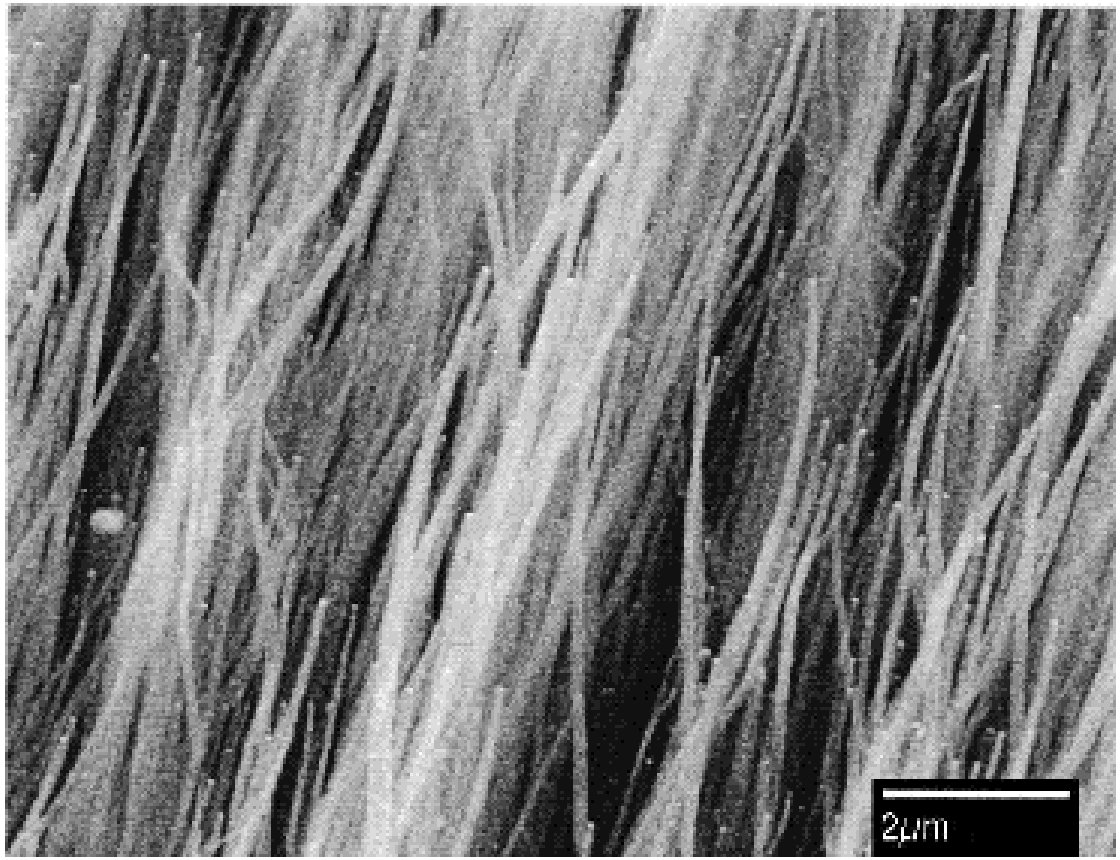


FIG. 3. SEM micrograph shows that carbon nanotubes with higher aspect ratios are synthesized using a higher plasma intensity than that used for the samples in Fig. 2. The length of the carbon nanotubes is at least 10 μm and the diameters are <100 nm.

Conclusions

- We are homing in on attractive AFEA emitter materials/structures
- Given a stable and reliable AFEA, the massively parallel pixel imaging system is extremely promising for high-speed sub-80 nm lithography (60 wafers per hour, easy!!)