Fabrication of micrometer-sized conical field emitters using femtosecond laser-assisted etching of silicon

James Carey

June 4, 2001

Outline

Introduction

- **fabrication**
- **optical properties**

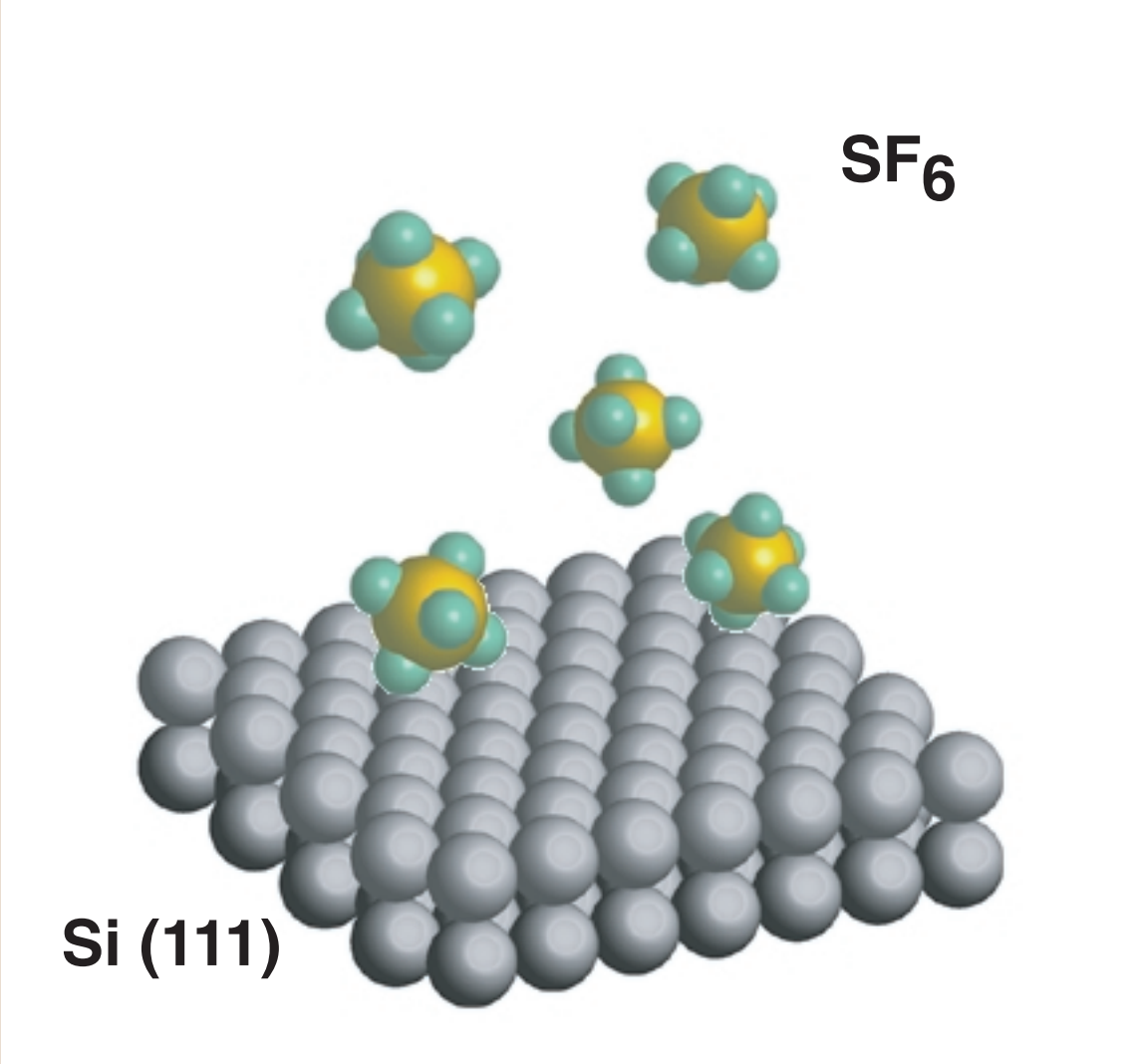
Field Emission

- **background**
- **Fowler-Nordheim**

Results

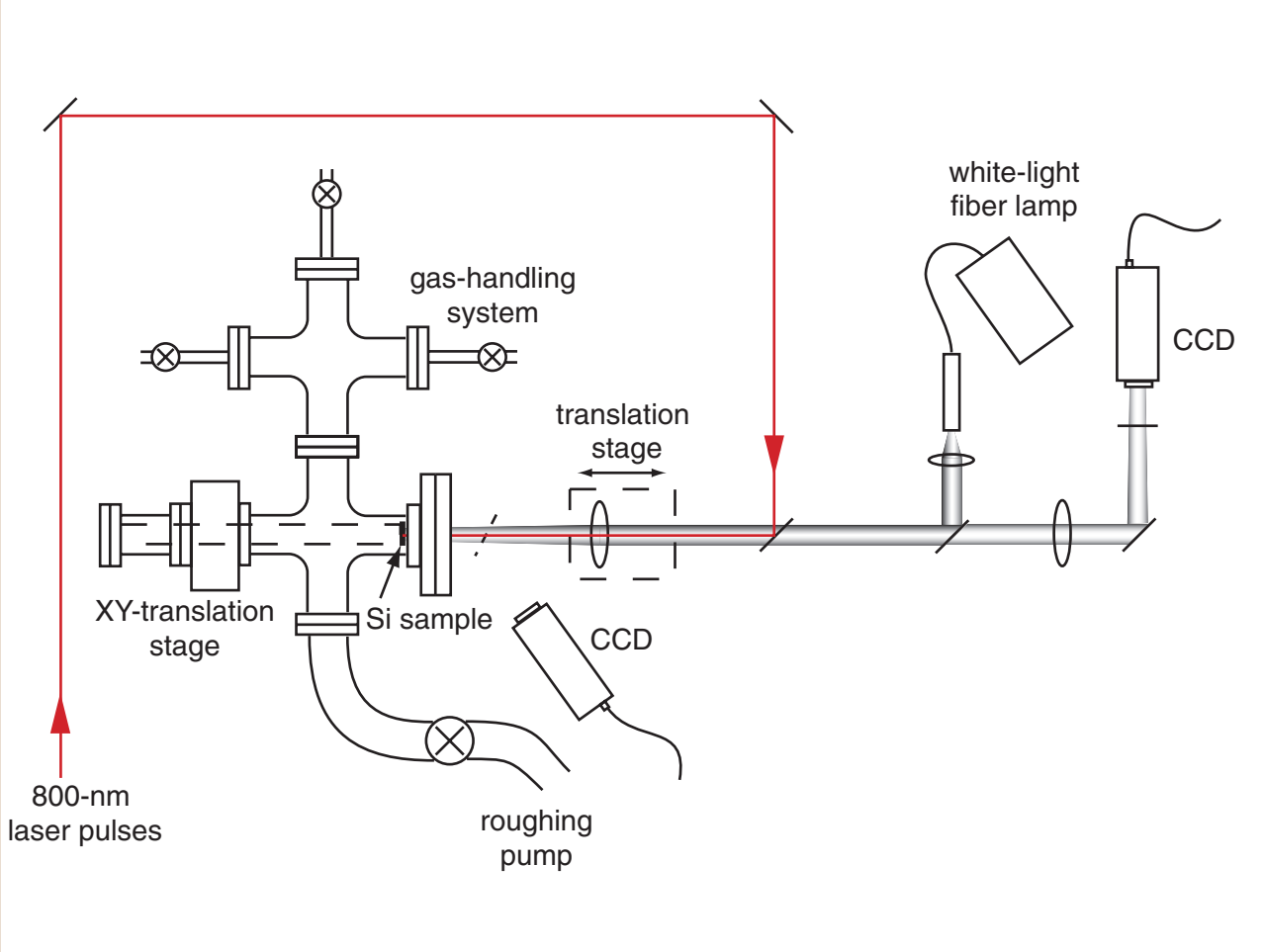
Discussion

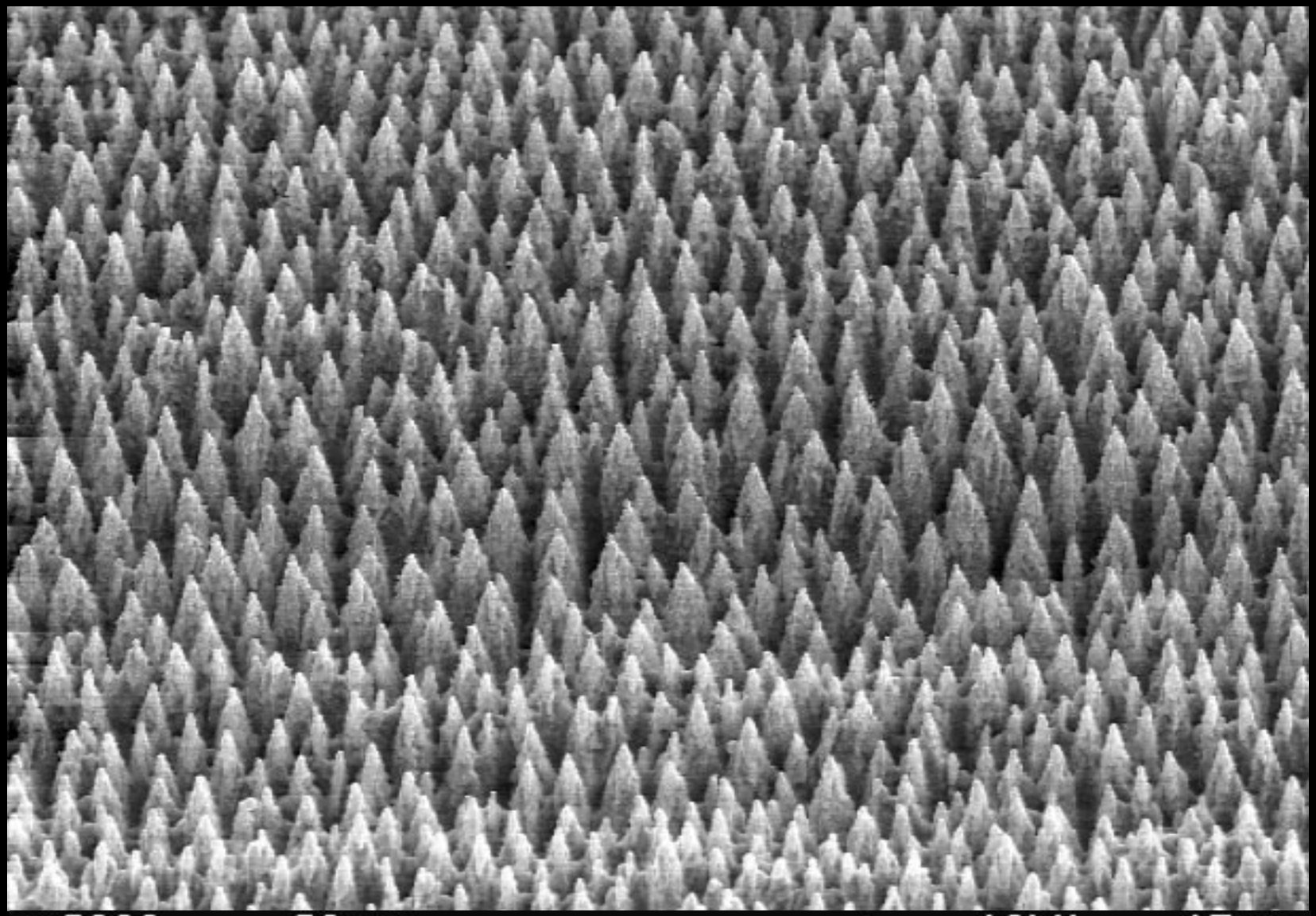
Introduction



irradiate with 100-fs 10 kJ/m^2 pulses

Fabrication setup

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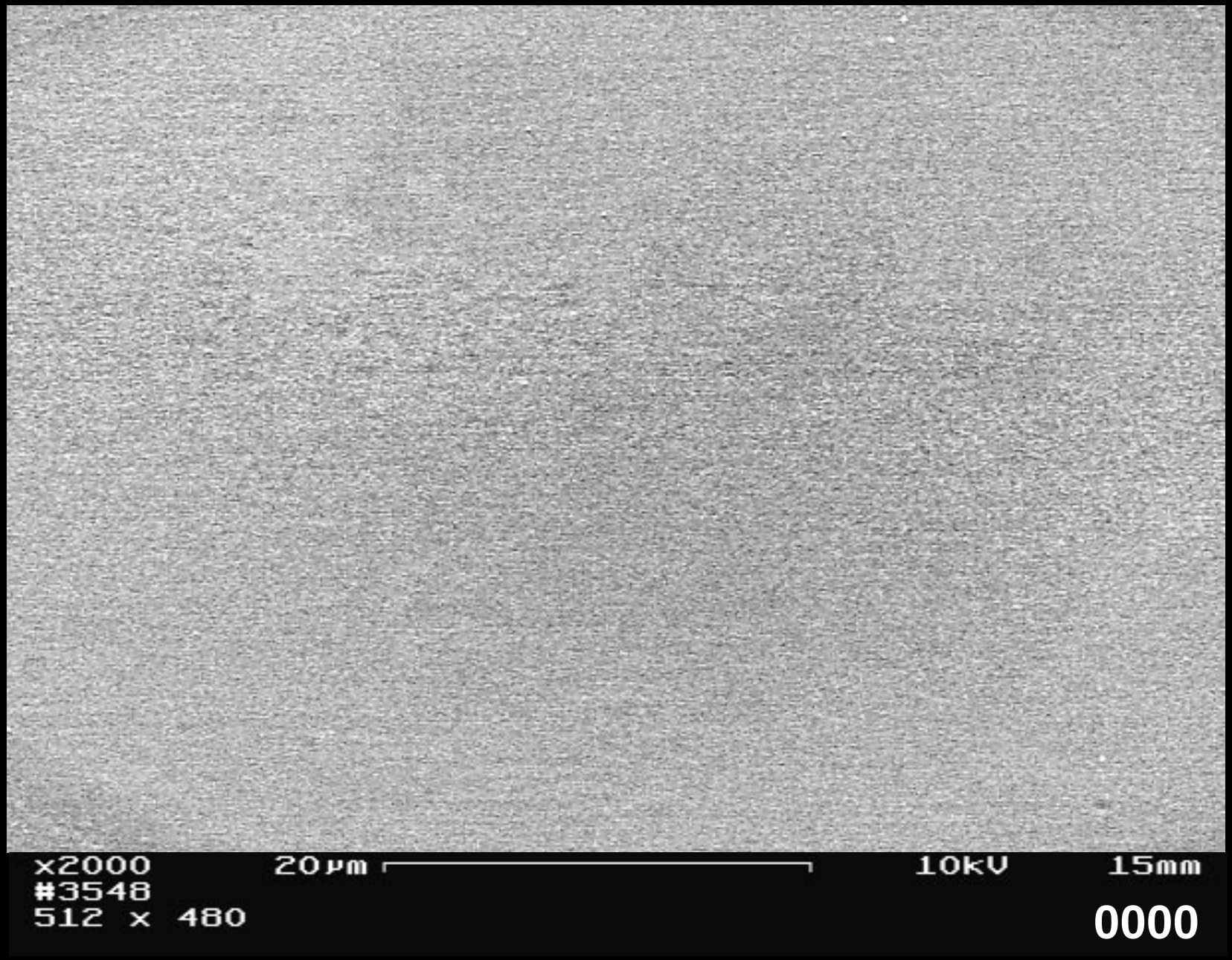
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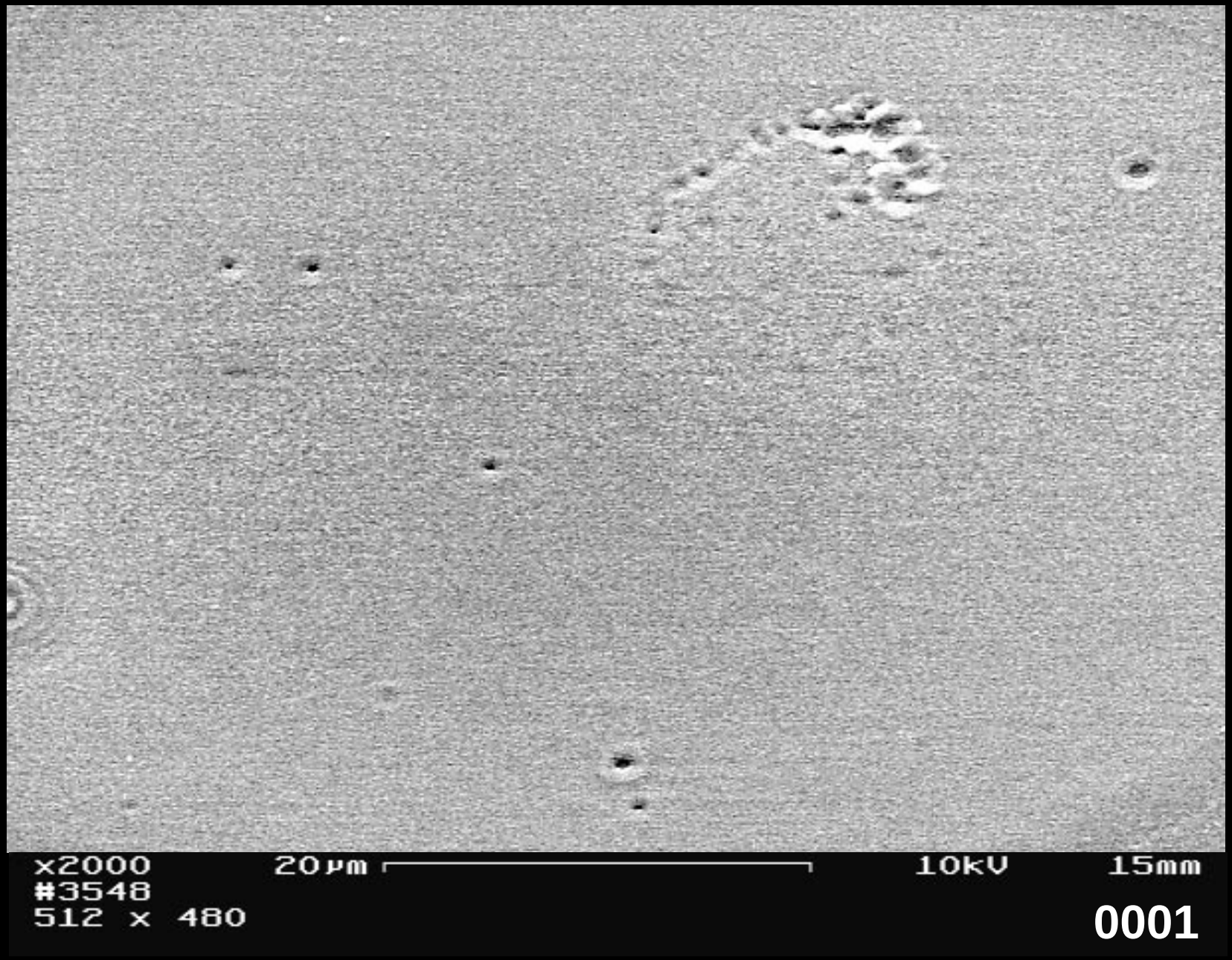
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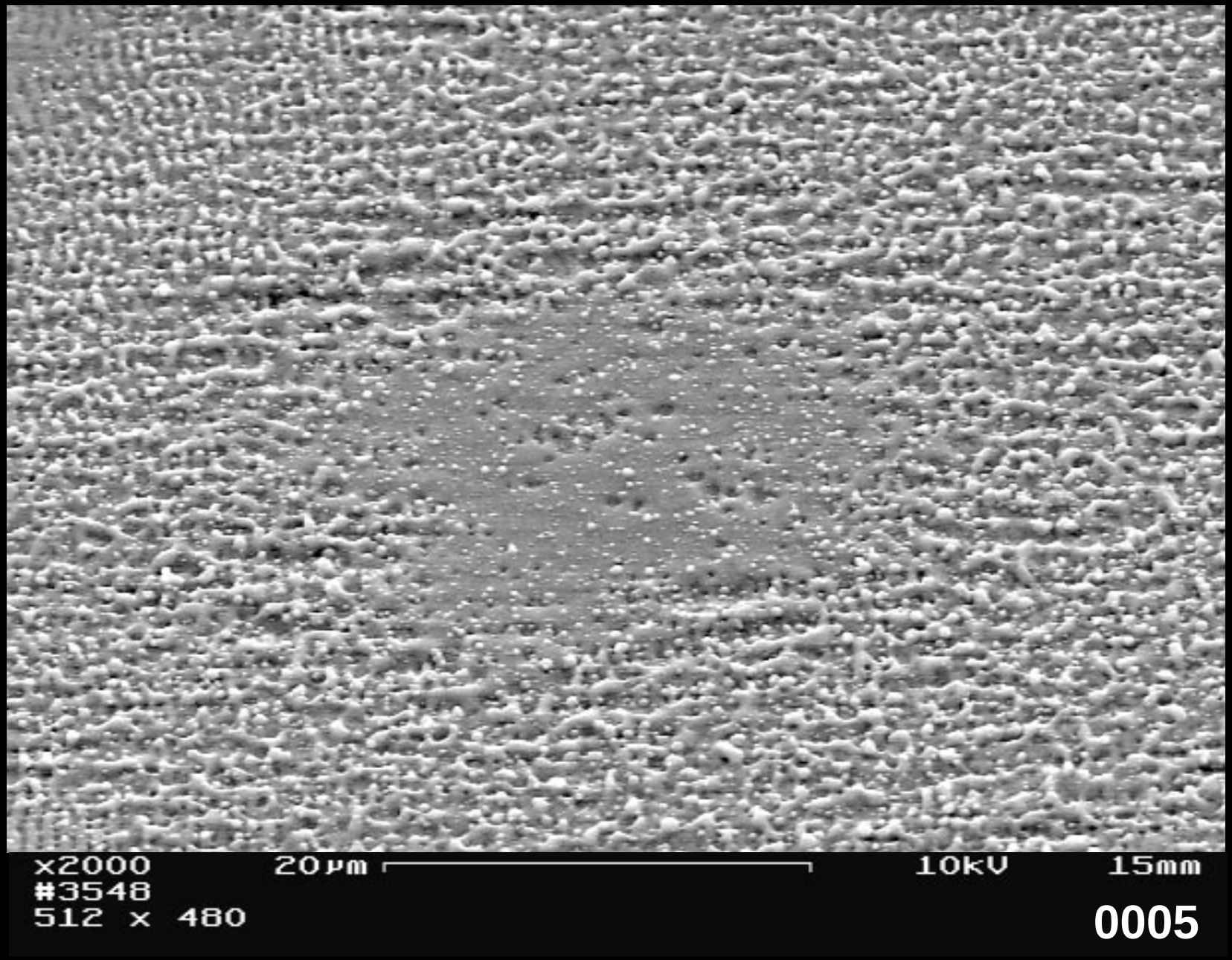
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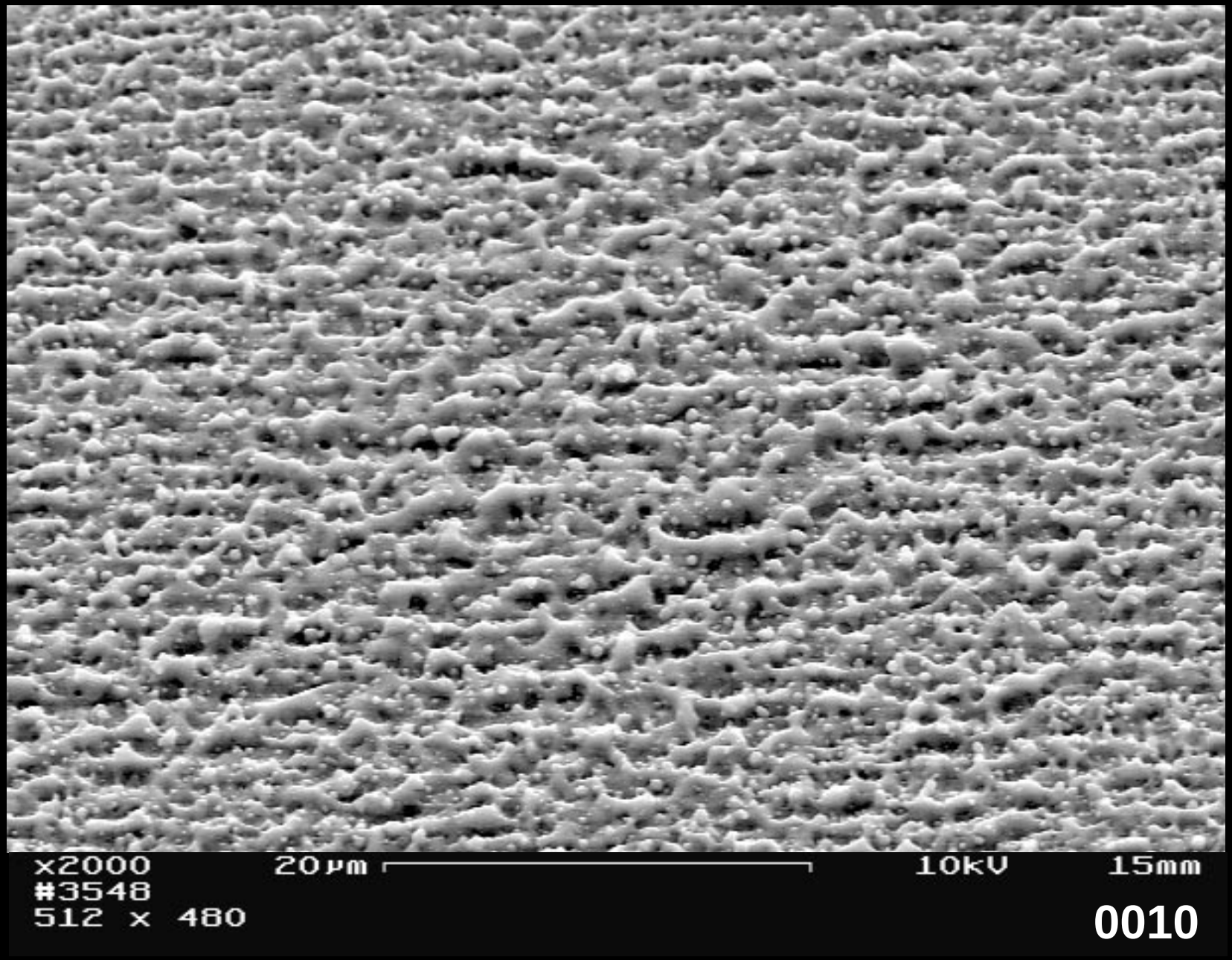
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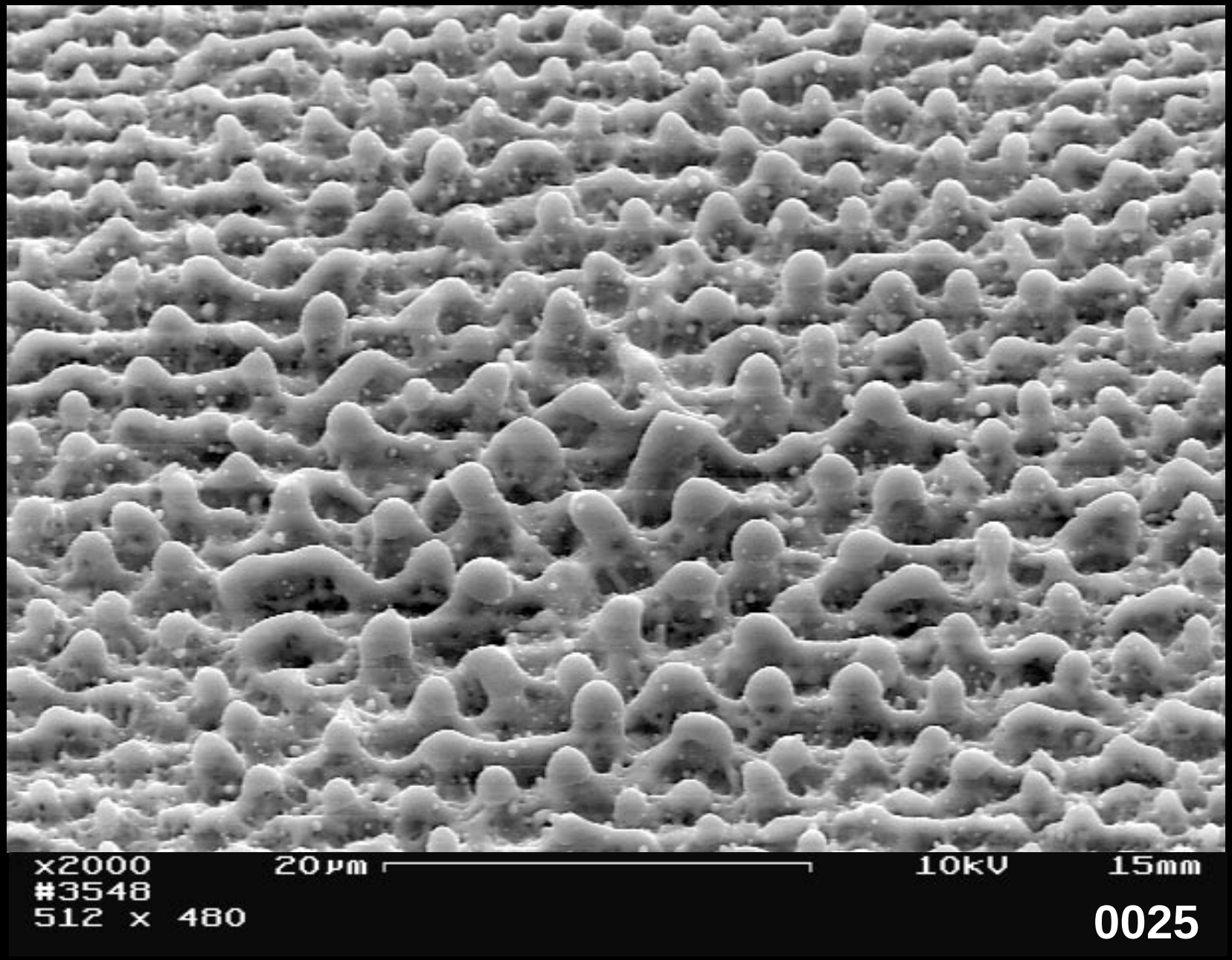
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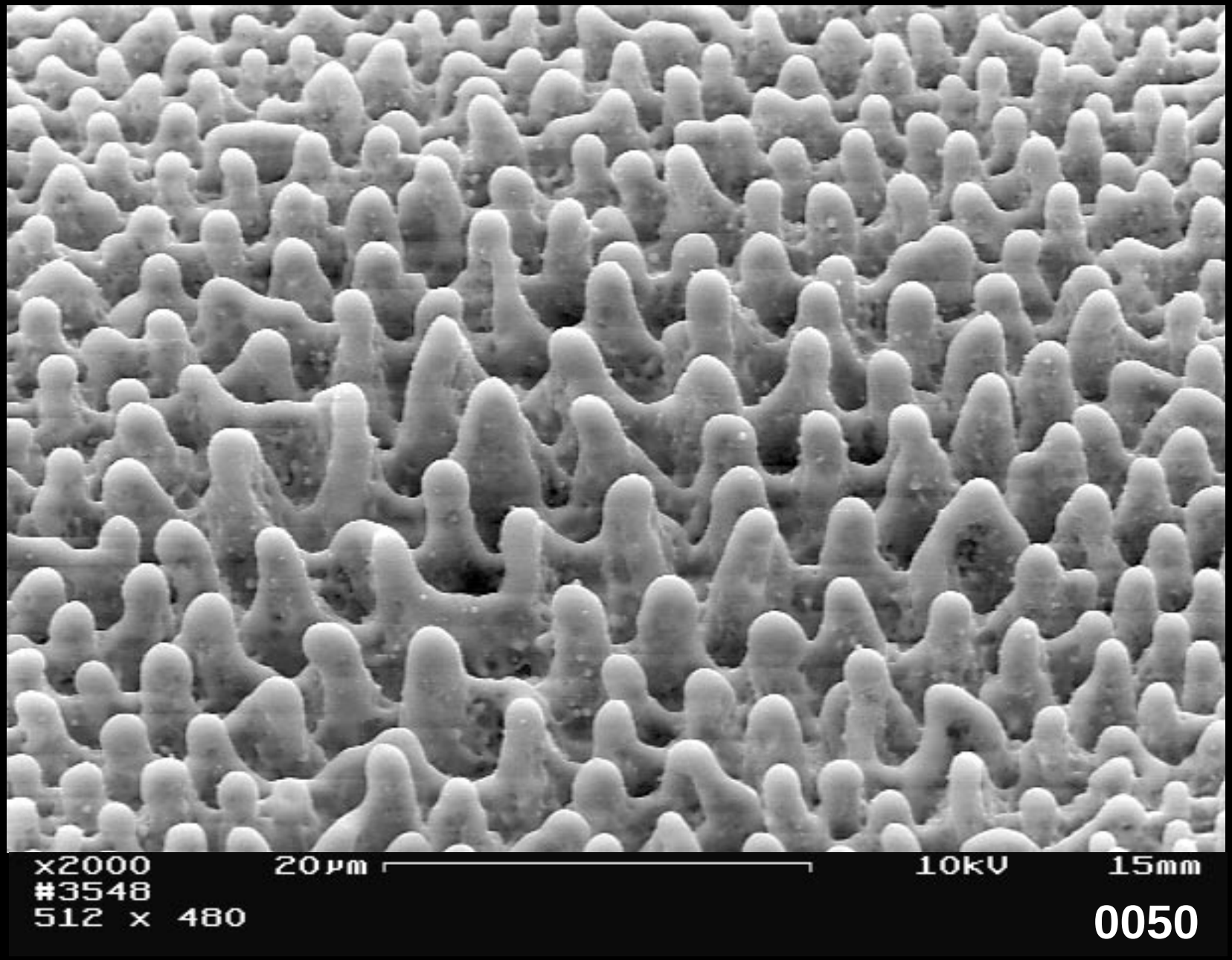
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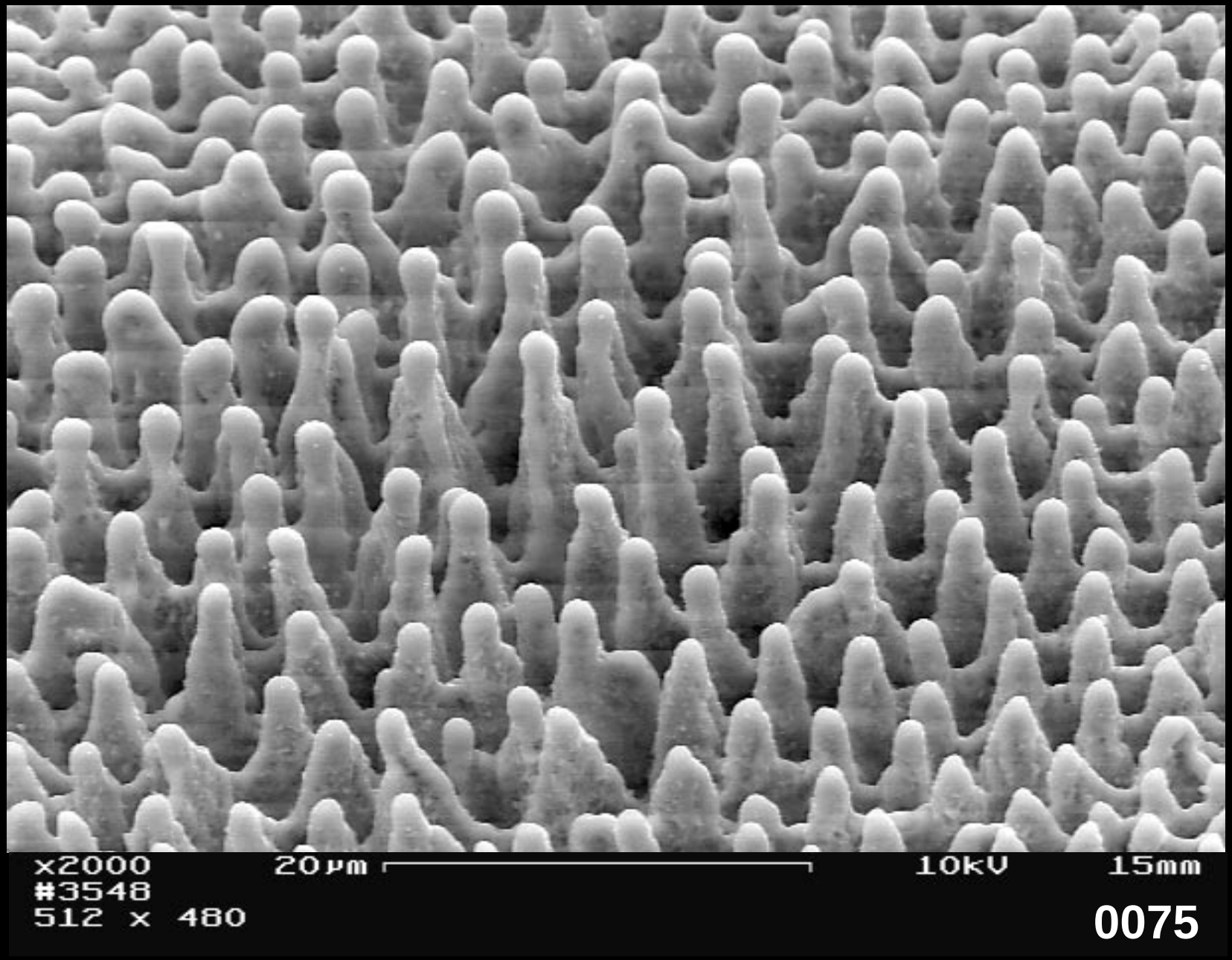
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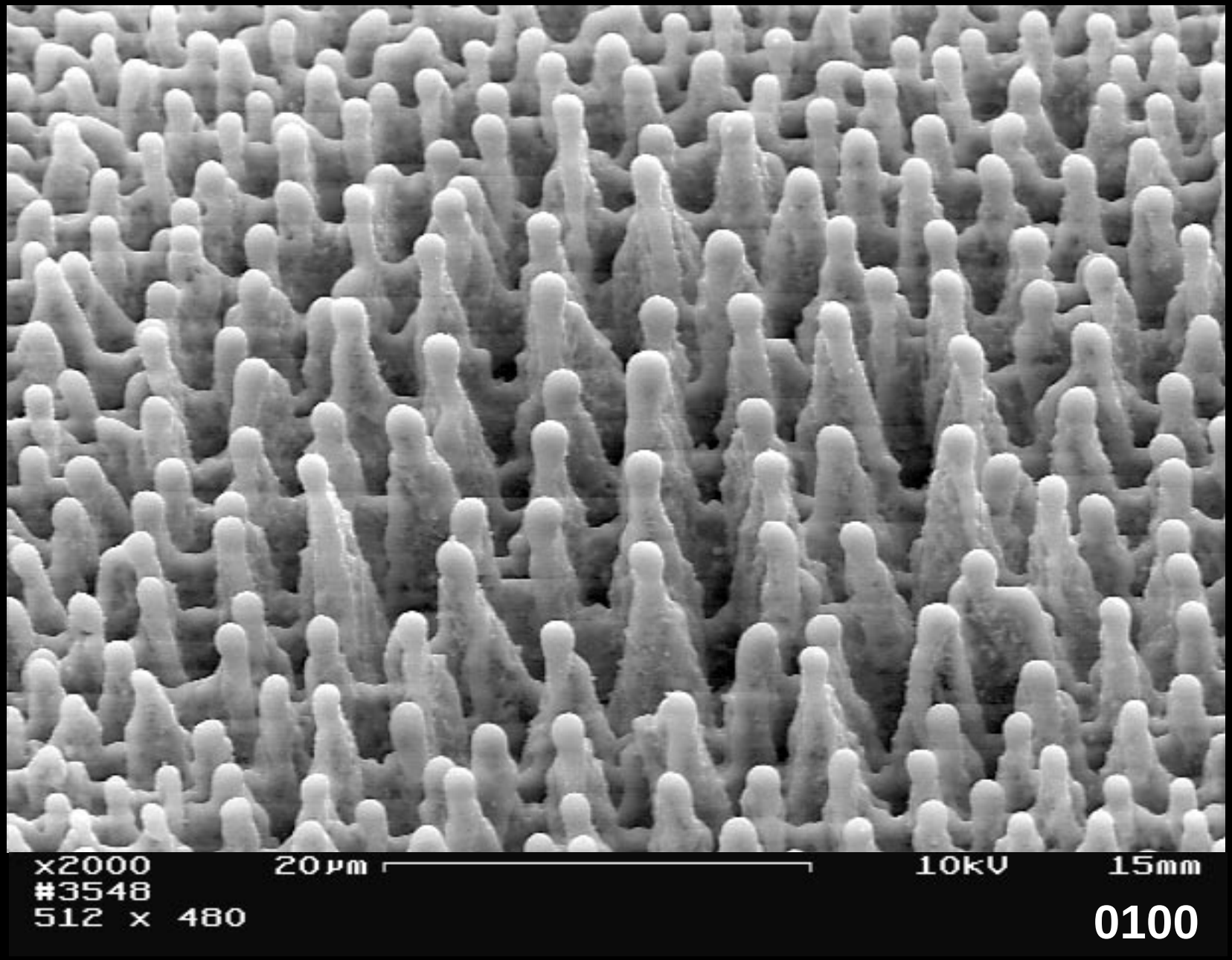
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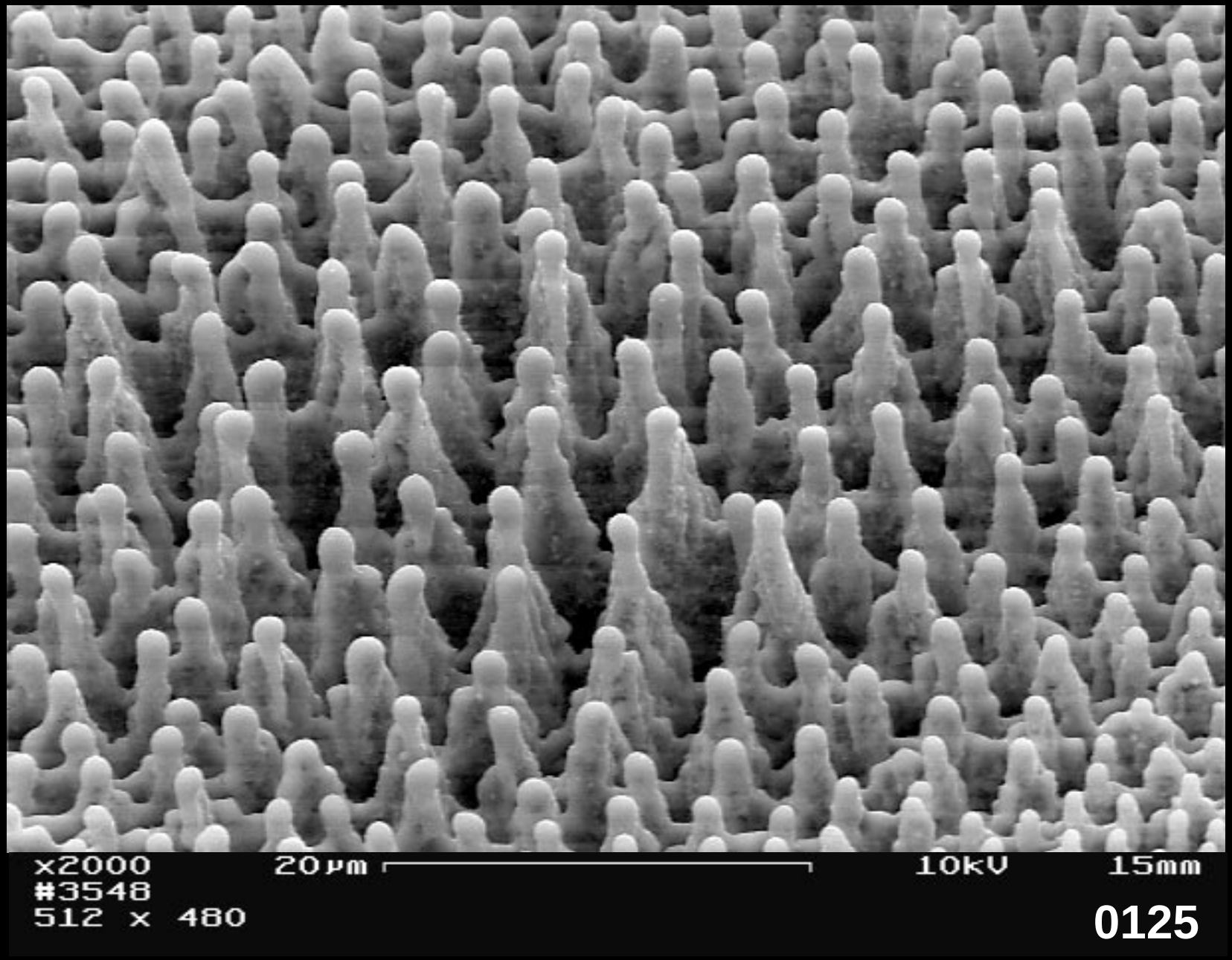
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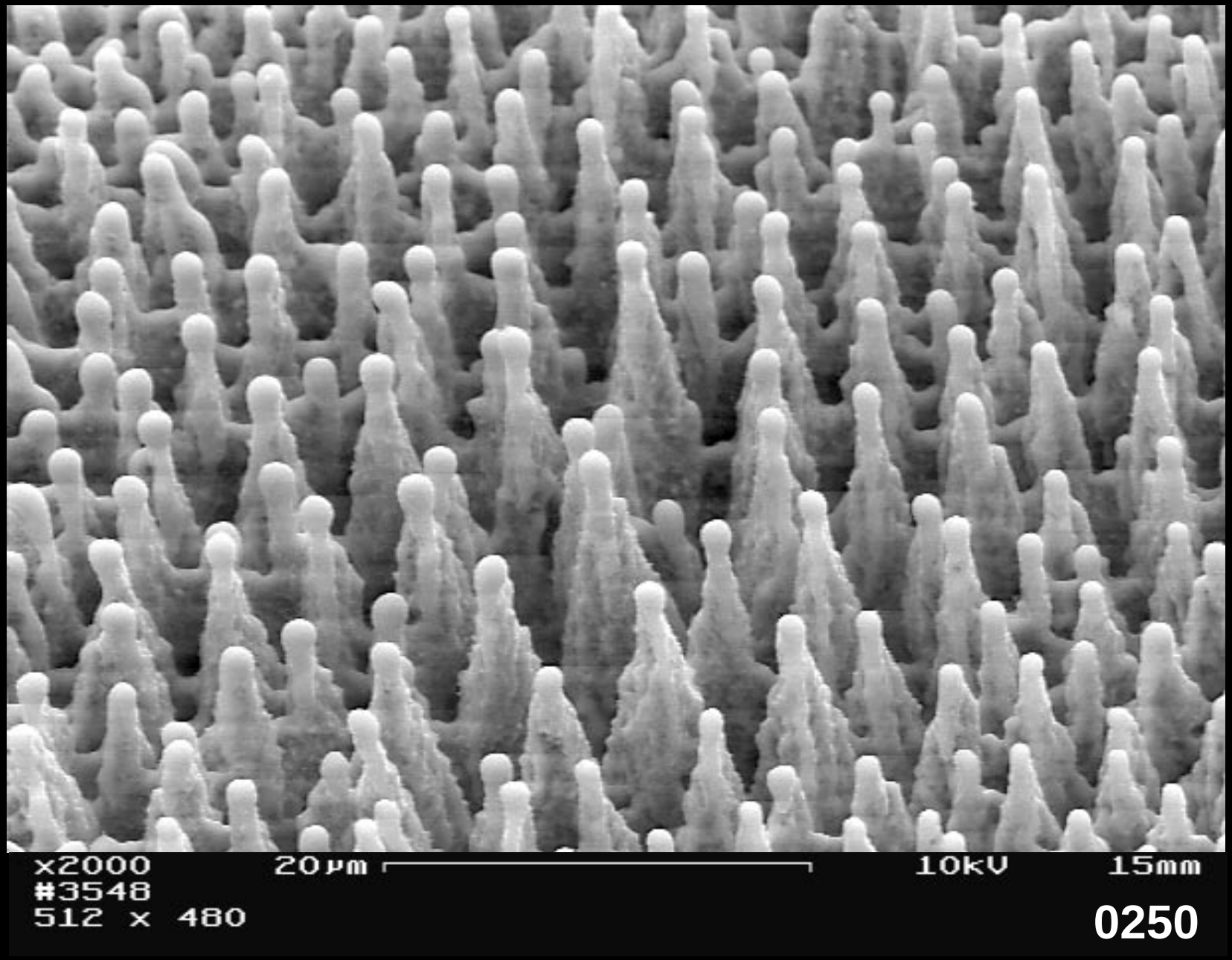
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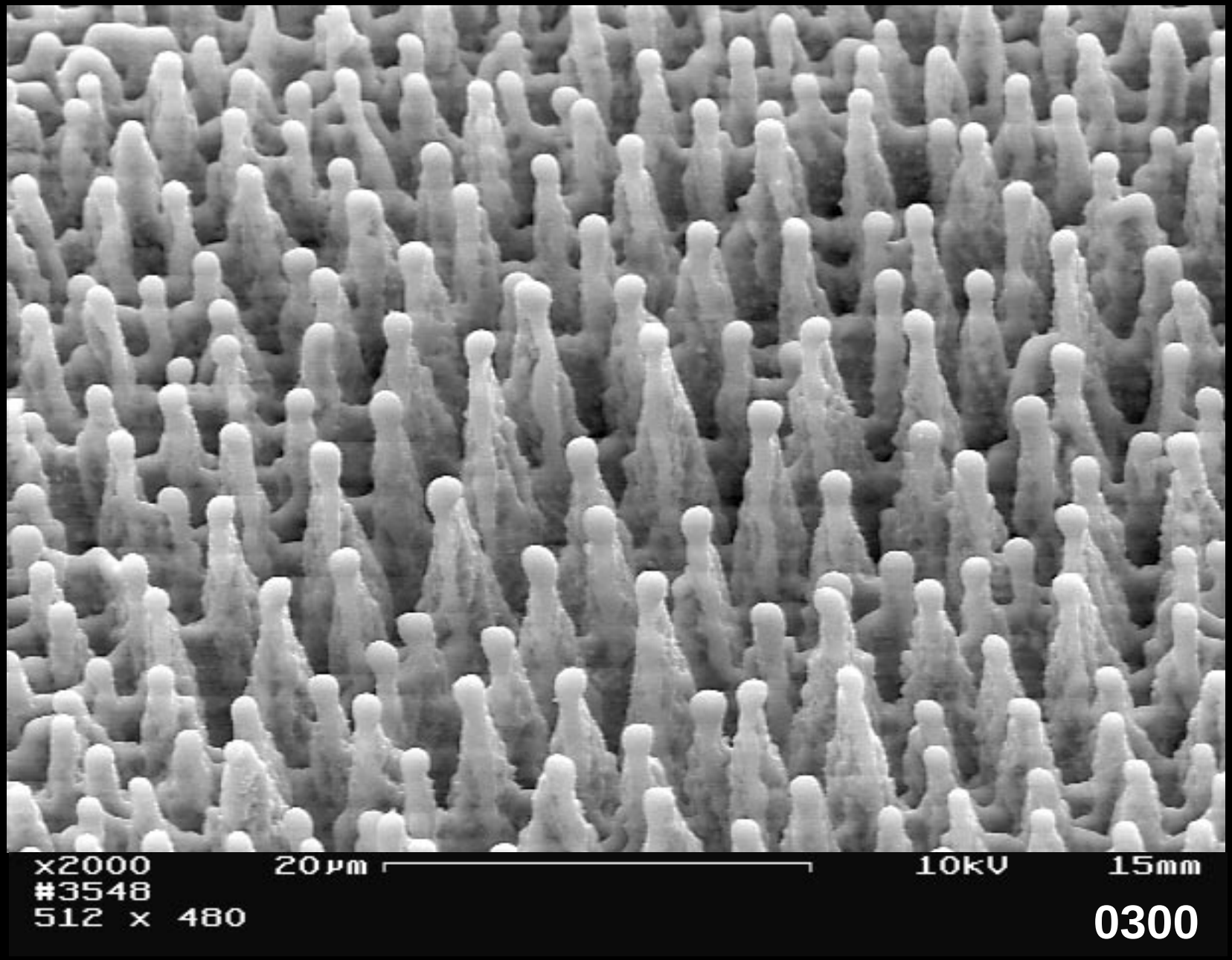
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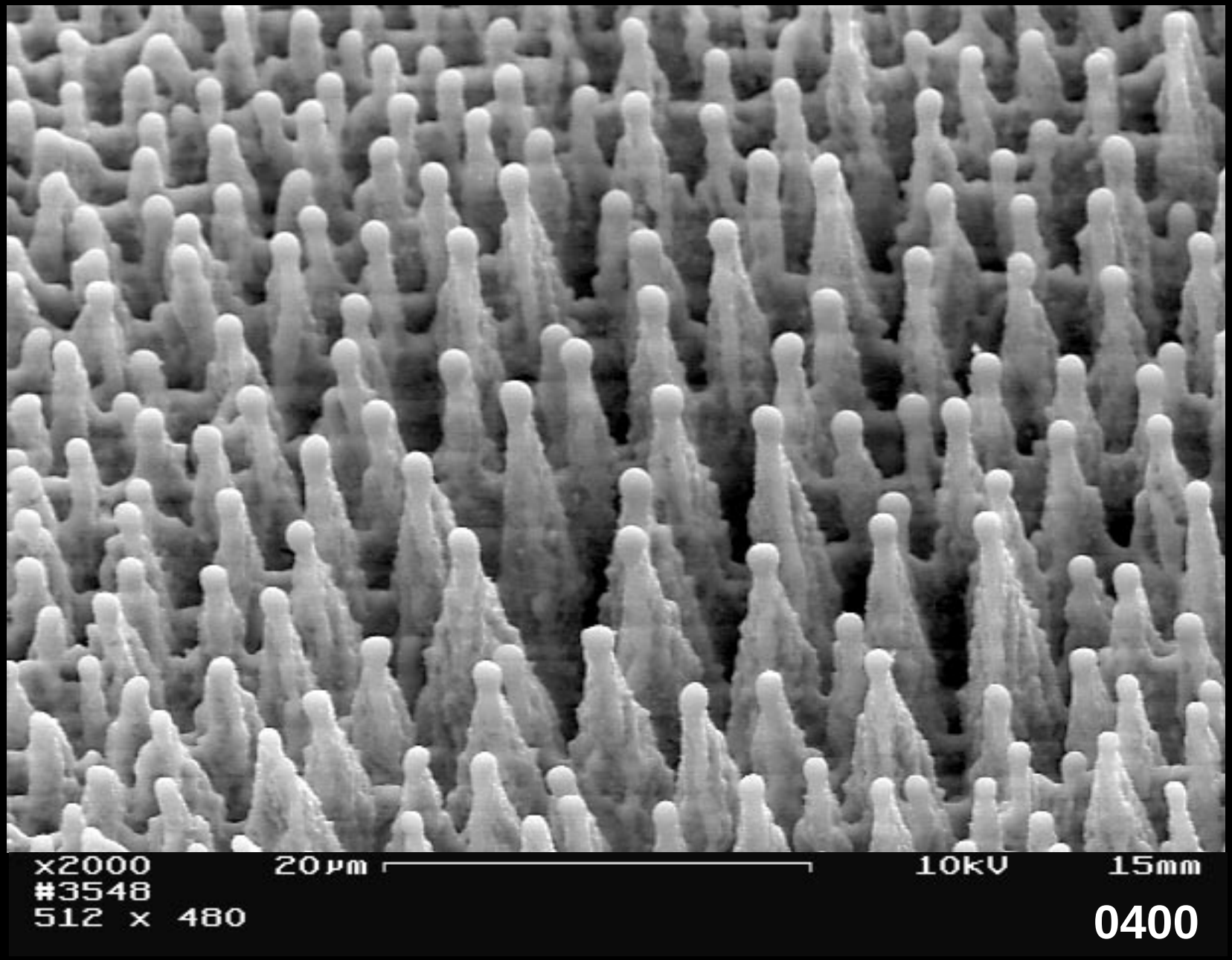
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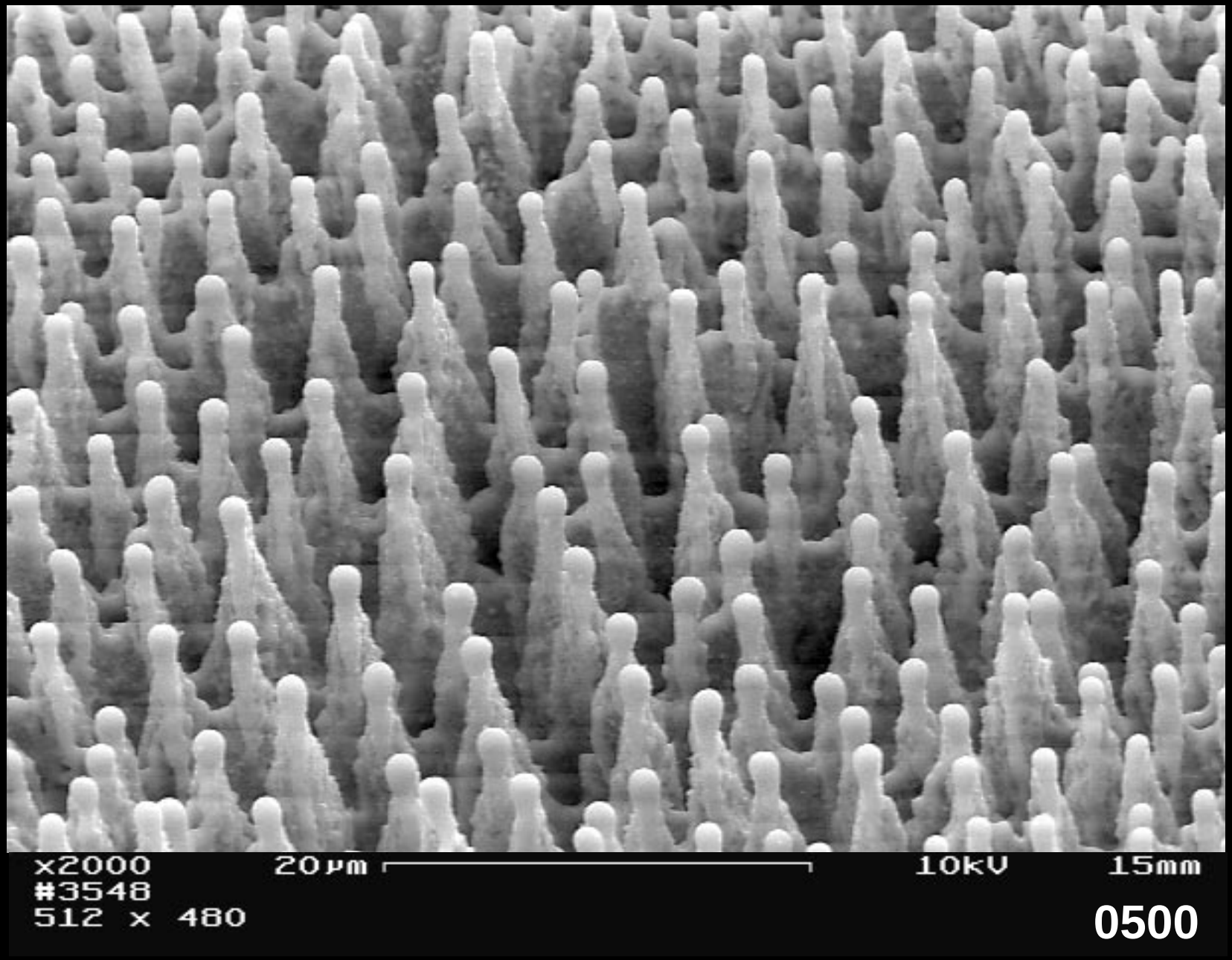
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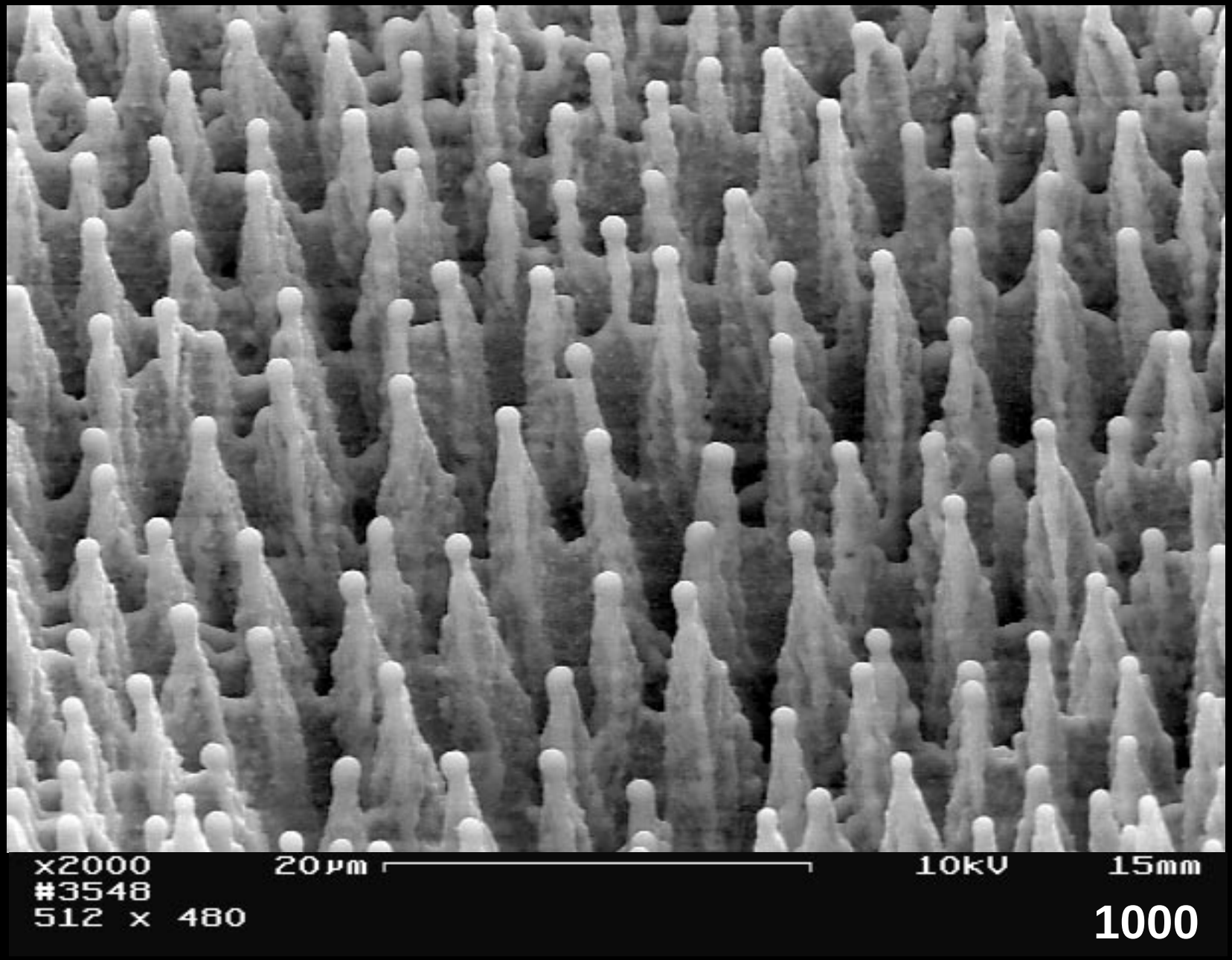
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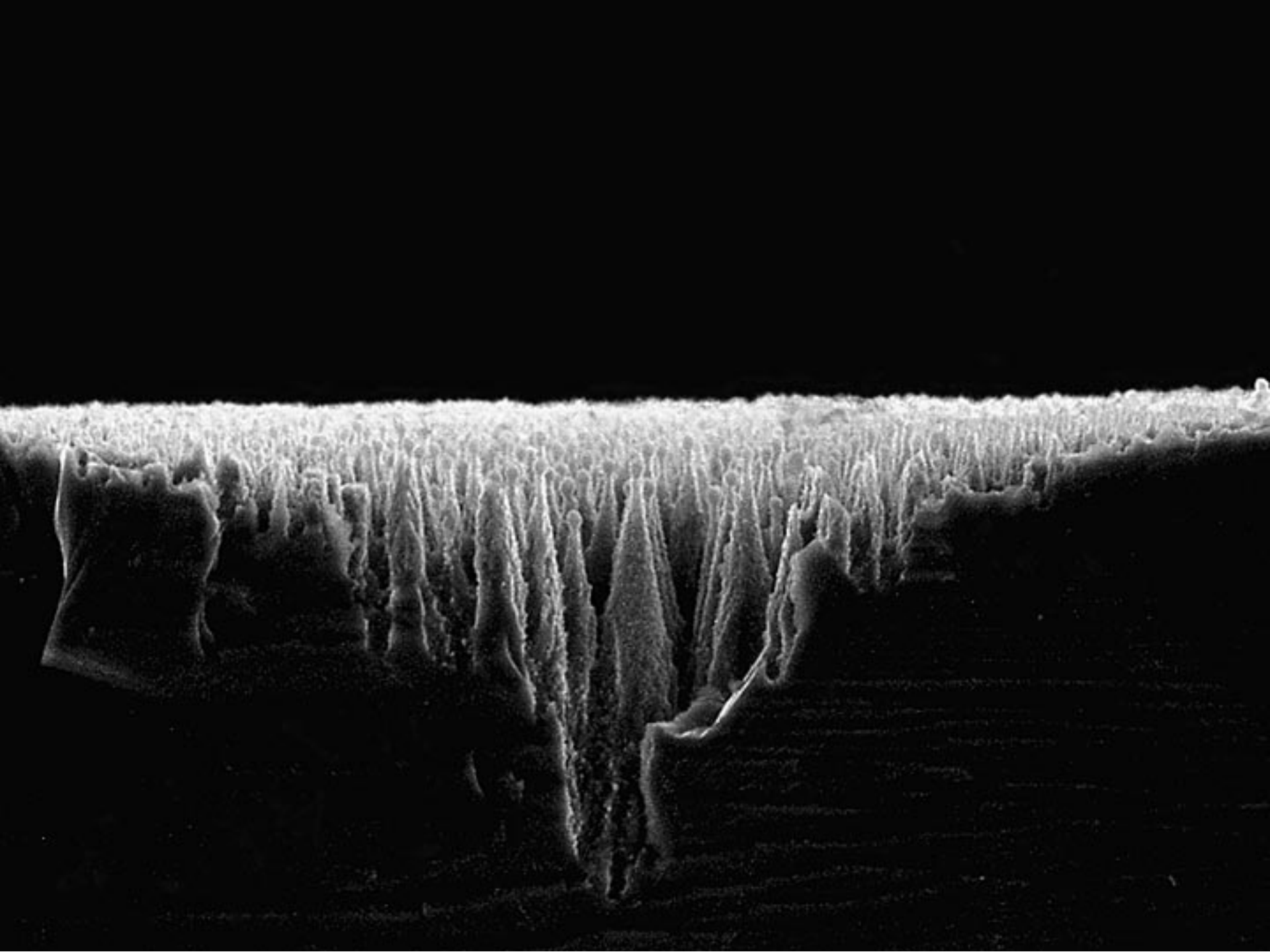
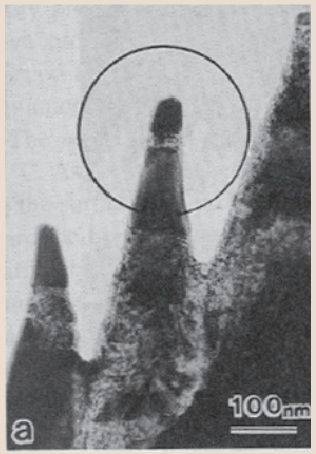
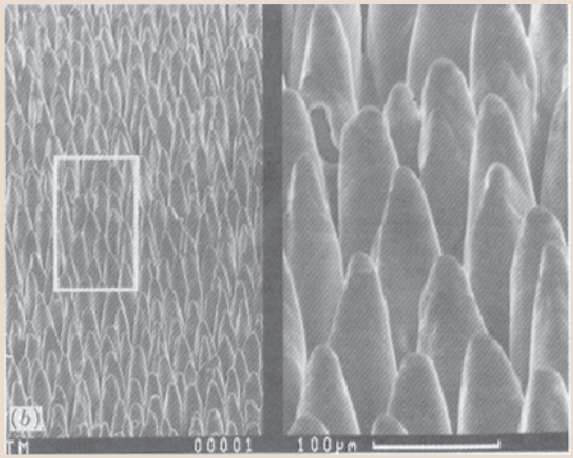
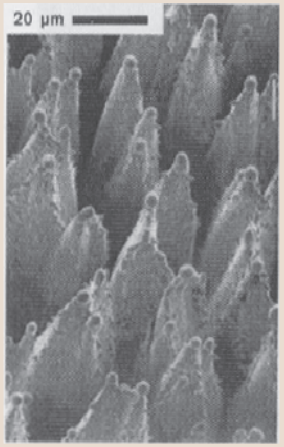


Introduction

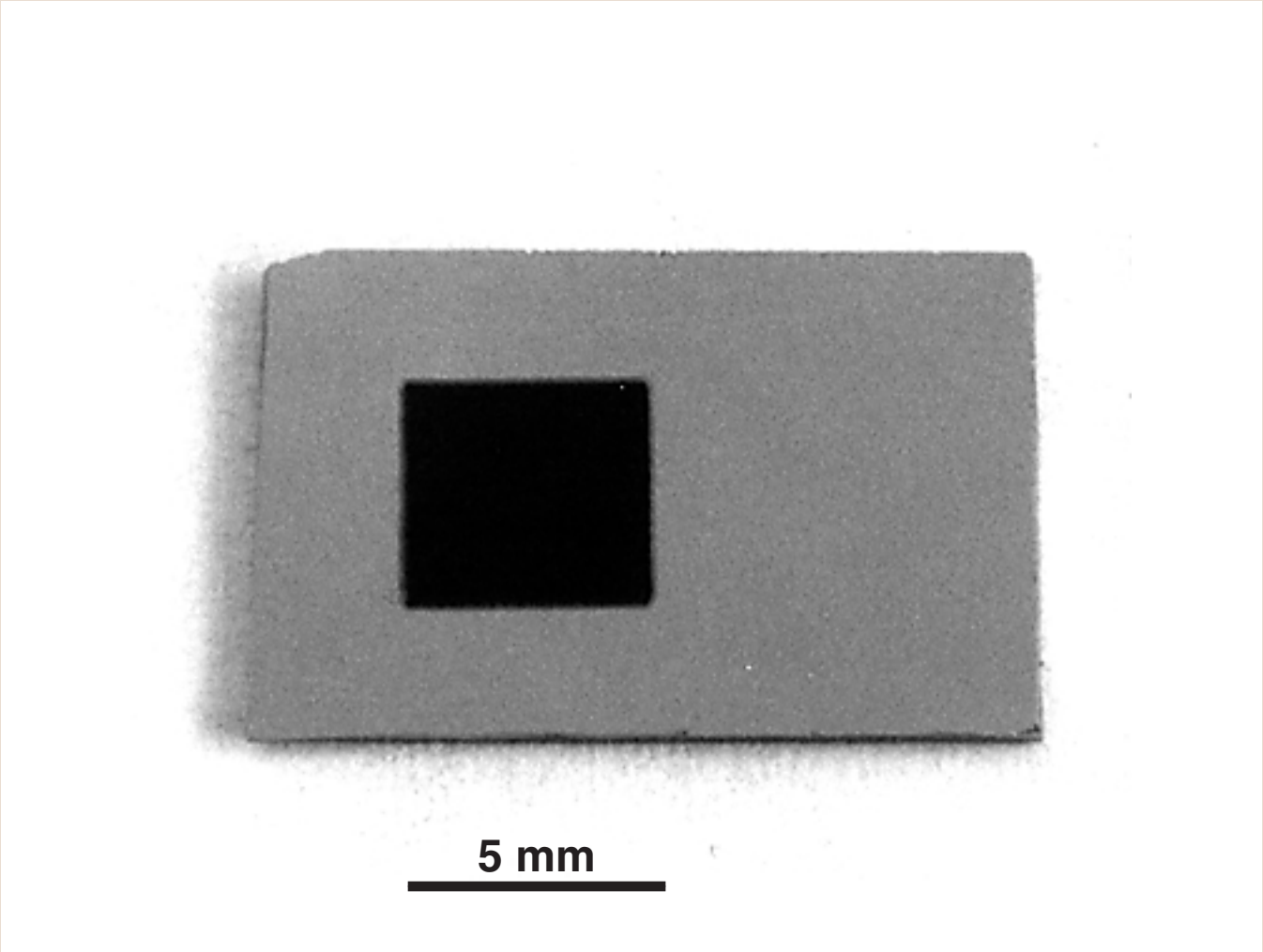






- **Sputter cones**
  - **Y. Fujimoto, M. Nozu, and F. Okuyama, J. Appl. Phys. 77, 2725 (1995)**
- **Laser cones from ns-pulses**
  - **D. Chrisey and G. Hubler, eds., *Pulsed Laser Deposition of Thin Films* (Wiley, NY, 1994), Ch. 4**
  - **A.J. Pedraza, J.D. Fowlkes, and D.H. Lowndes, Appl. Phys. Lett. 74, 2322 (1999)**

Introduction



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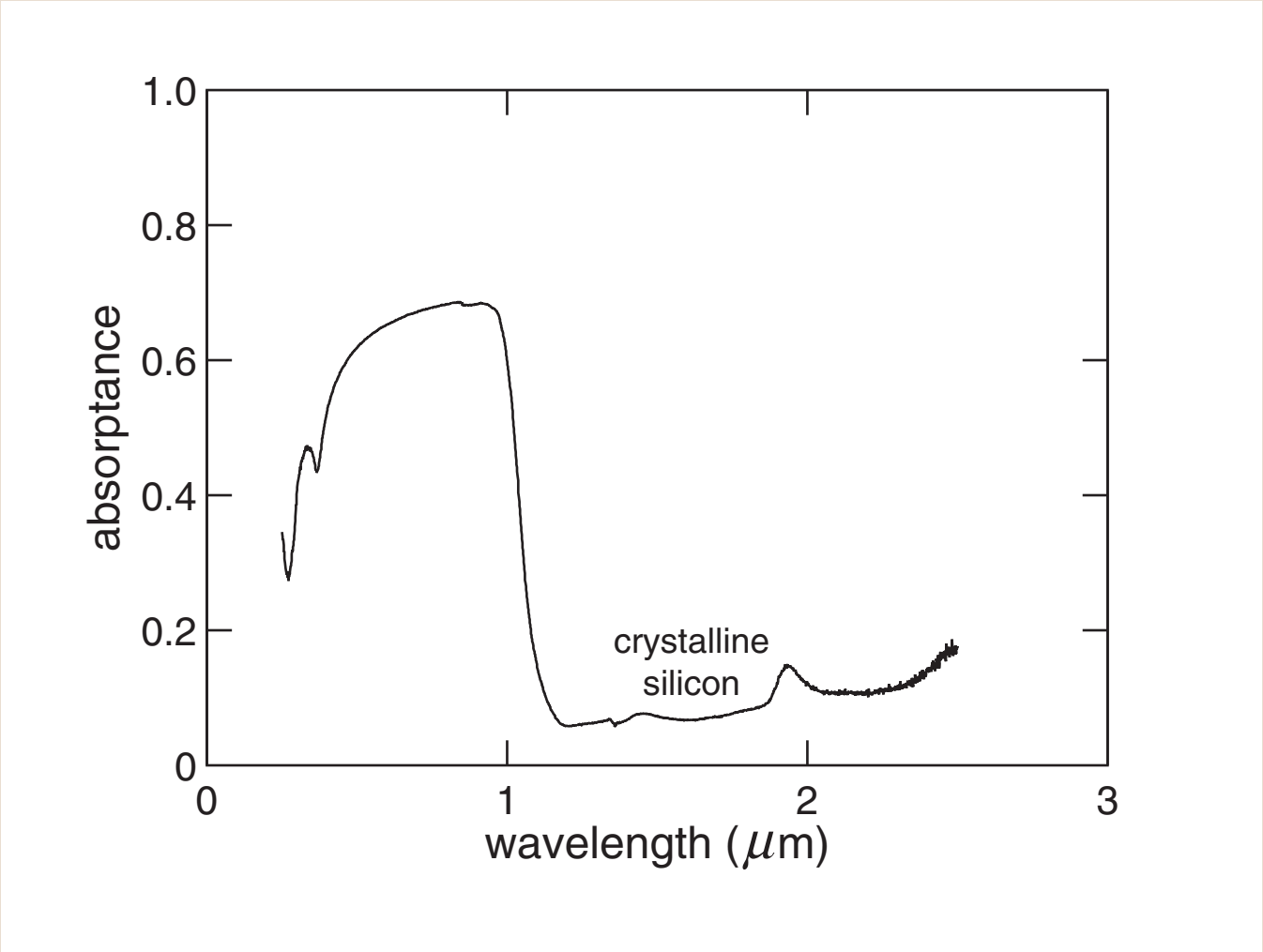

C. Wu, et al., Appl. Phys. Lett. 78, 1850 (2001)

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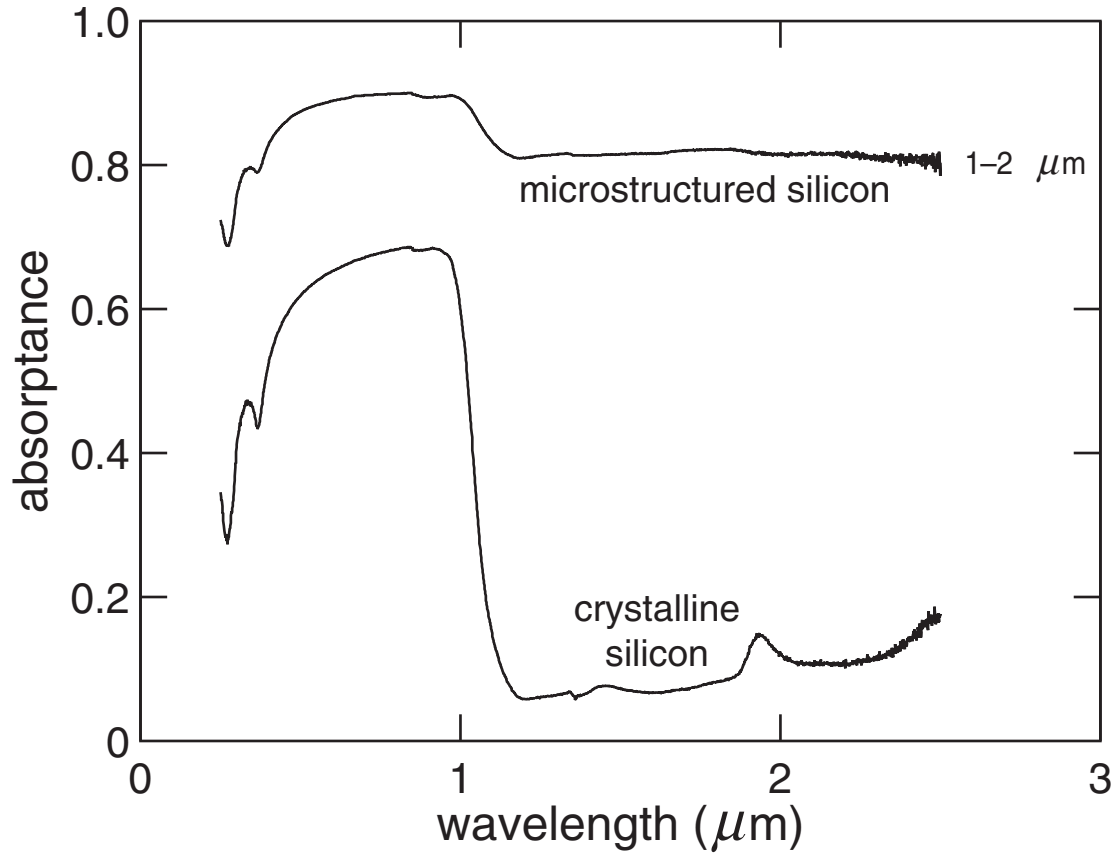

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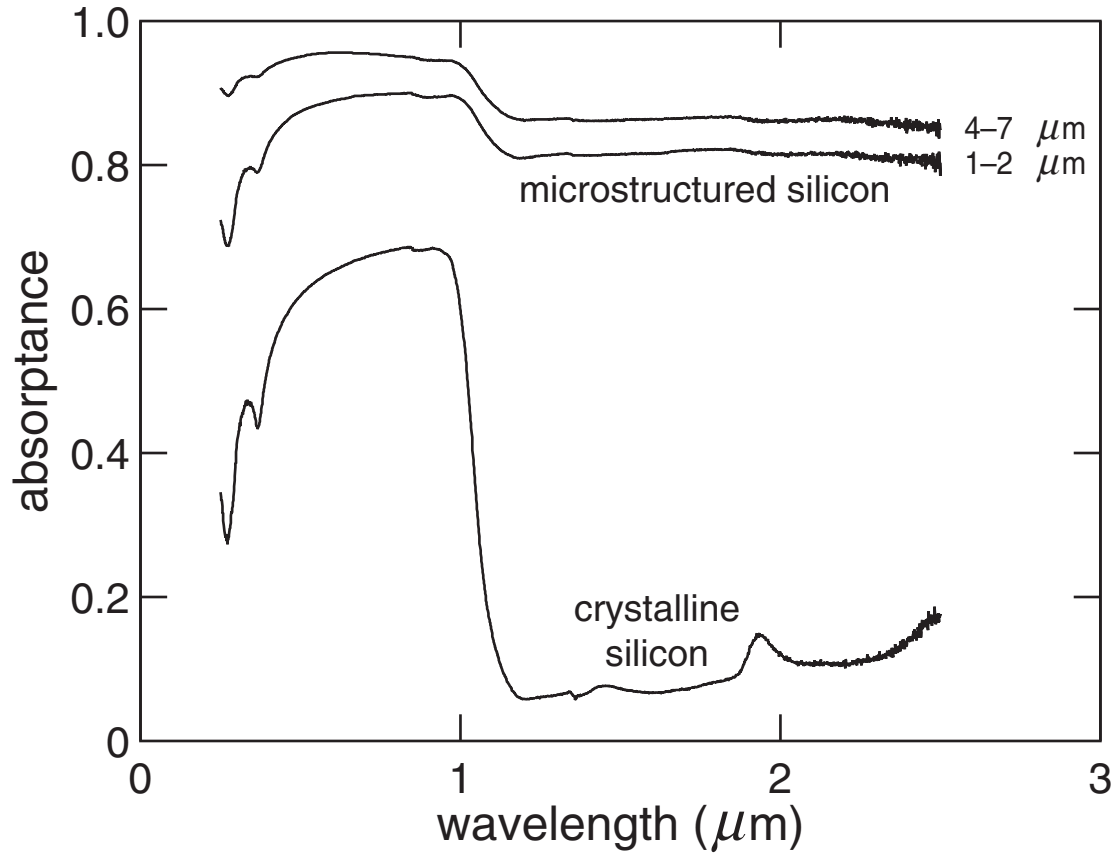

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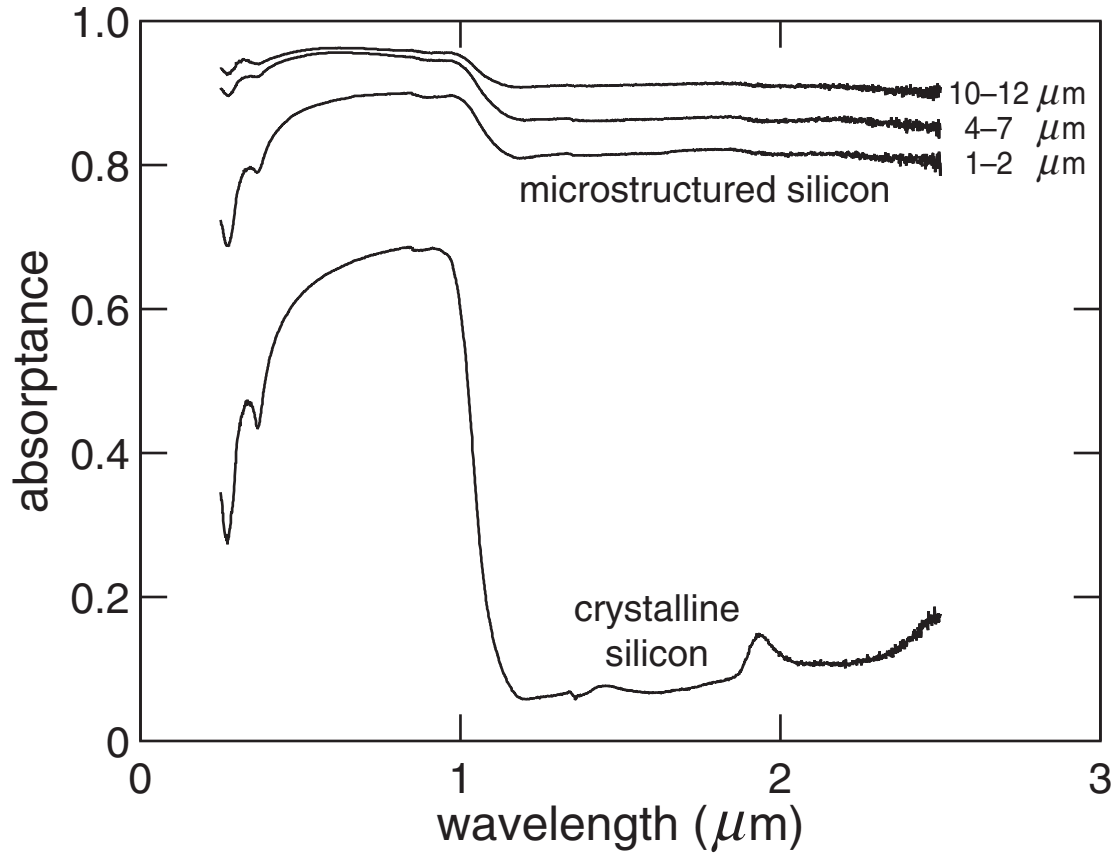
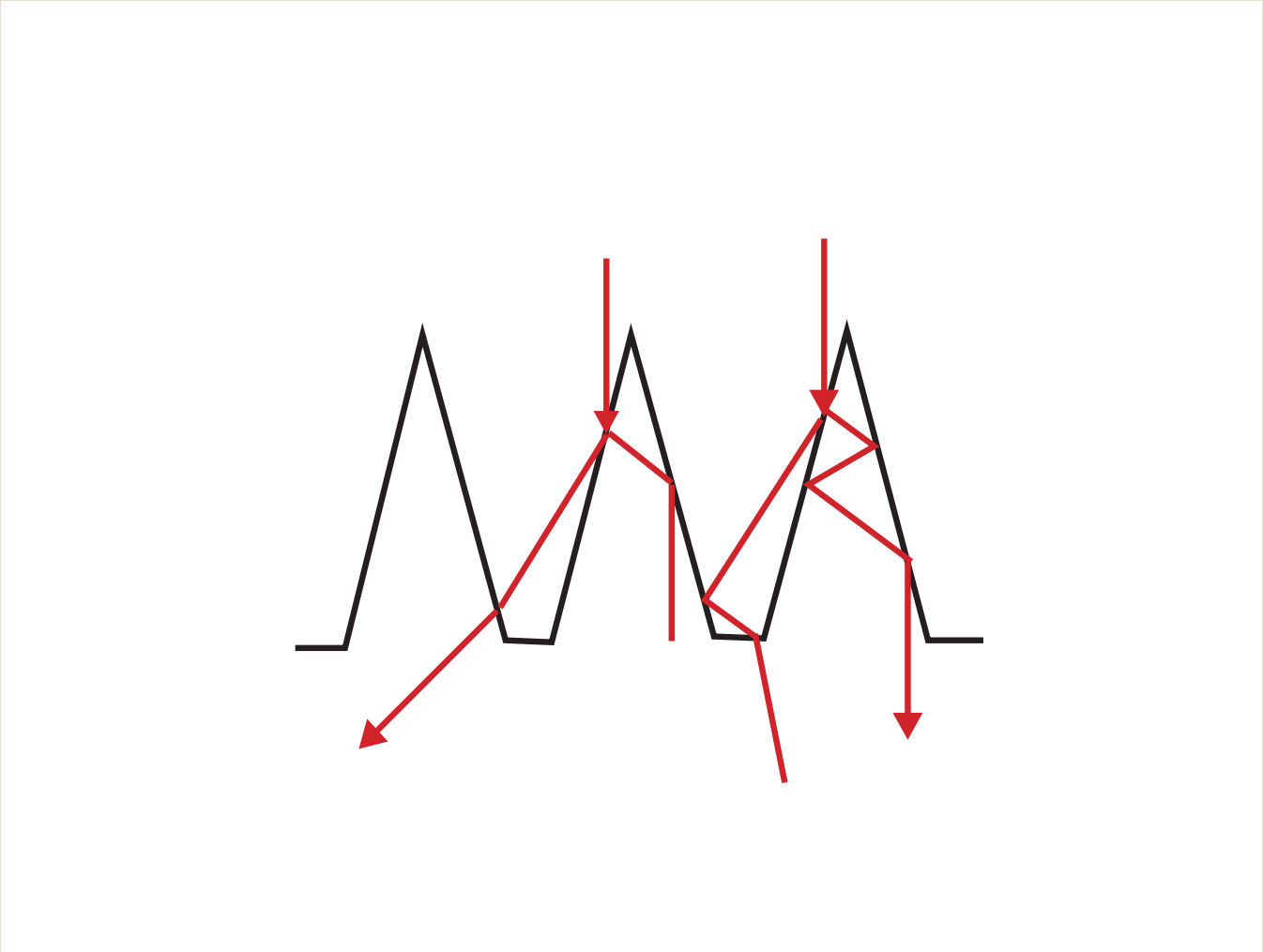


C. Wu, et al., Appl. Phys. Lett. 78, 1850 (2001)

Multiple reflections



Important properties

- **one step, maskless process**
- **large area with high density of microstructures**
- **band structure change**

Outline

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- fabrication
- optical properties

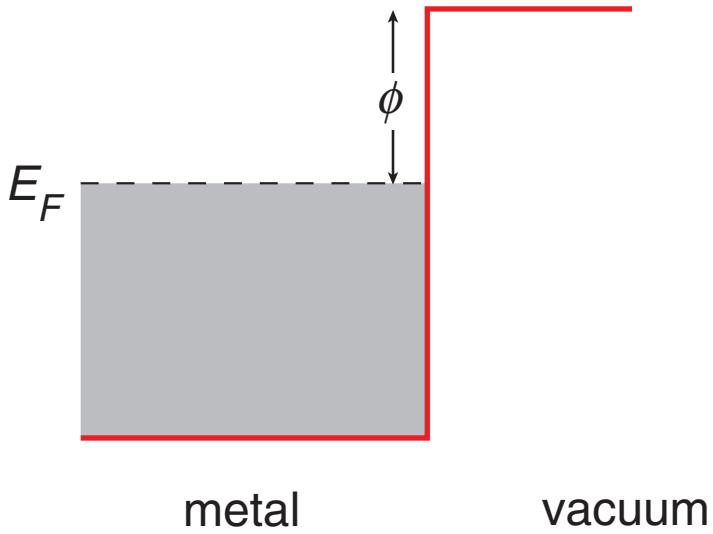
Field Emission

- **background**
- Fowler-Nordheim

Results

Discussion

Field Emission



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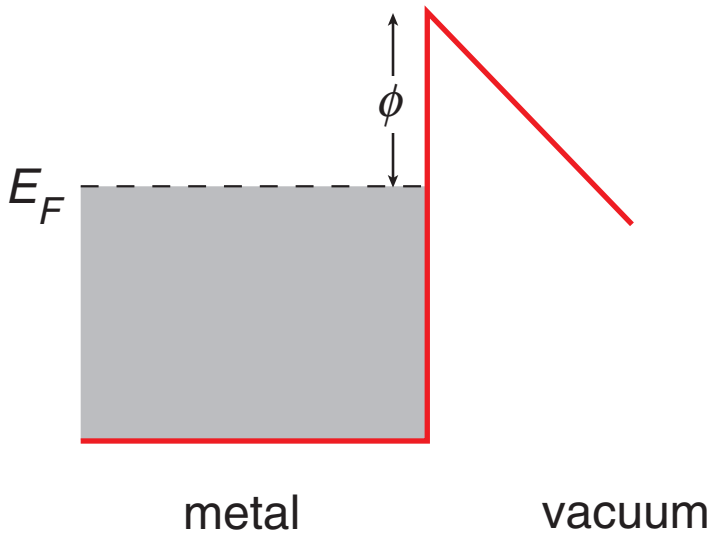

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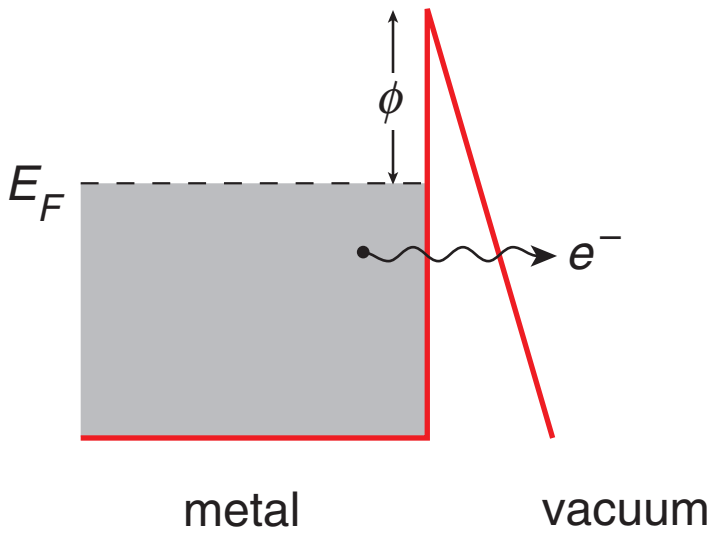

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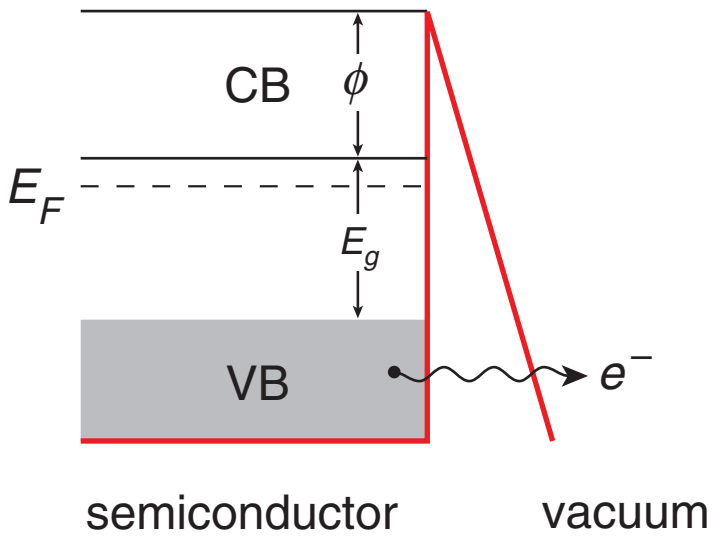

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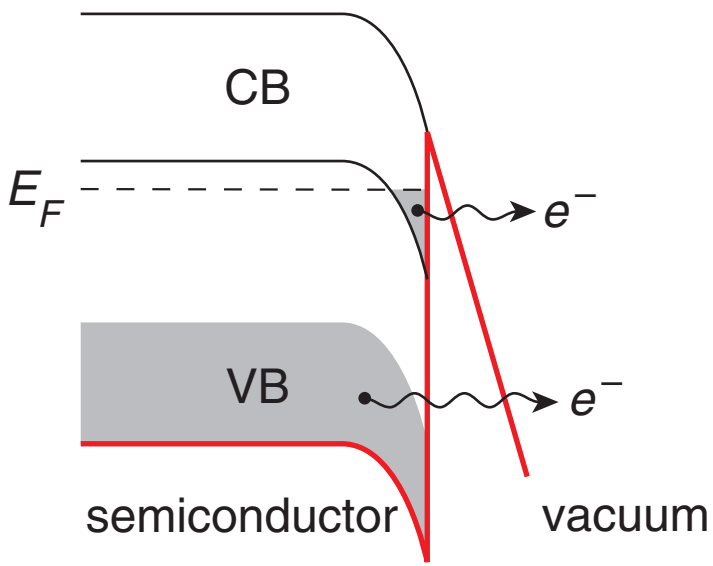

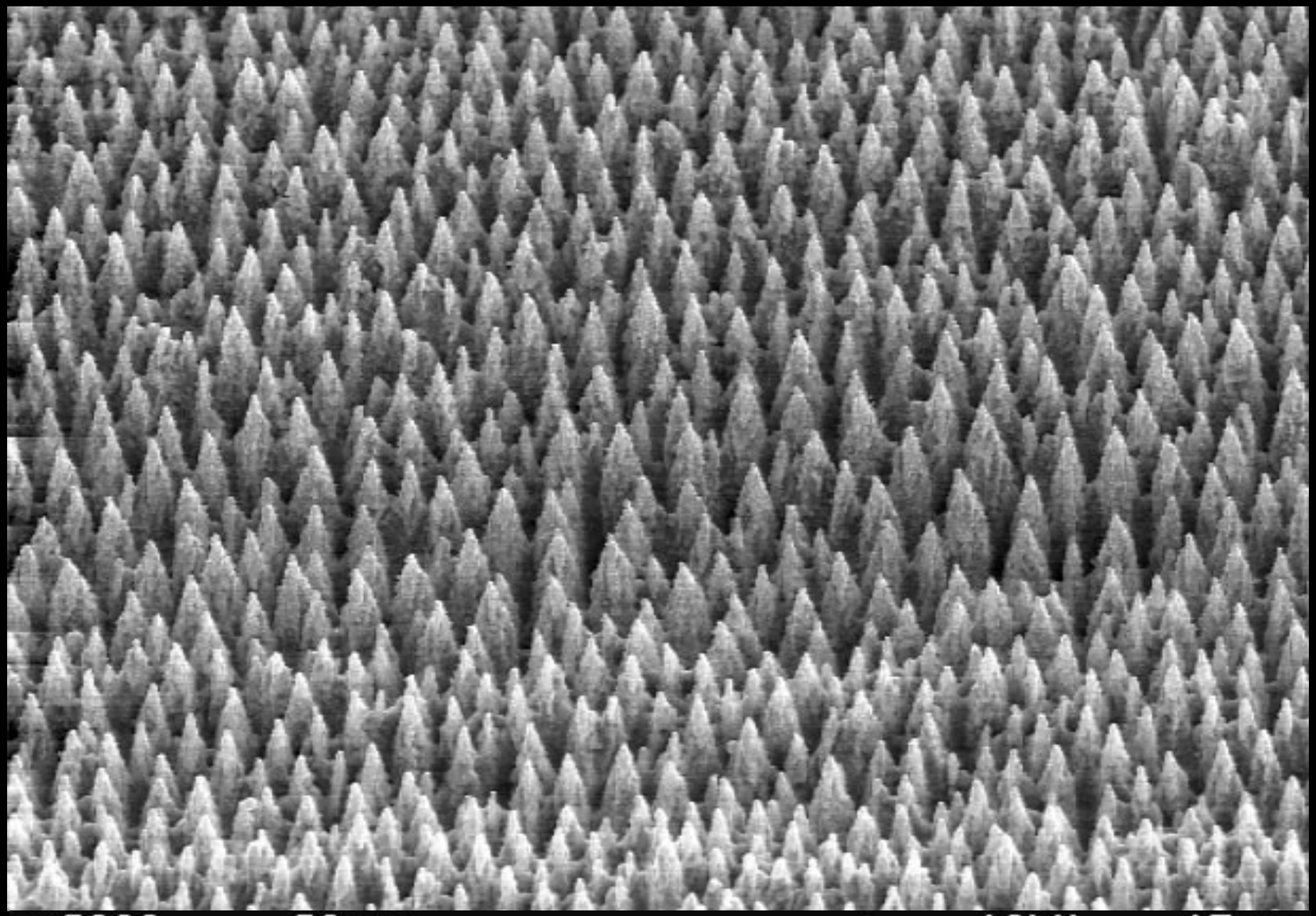
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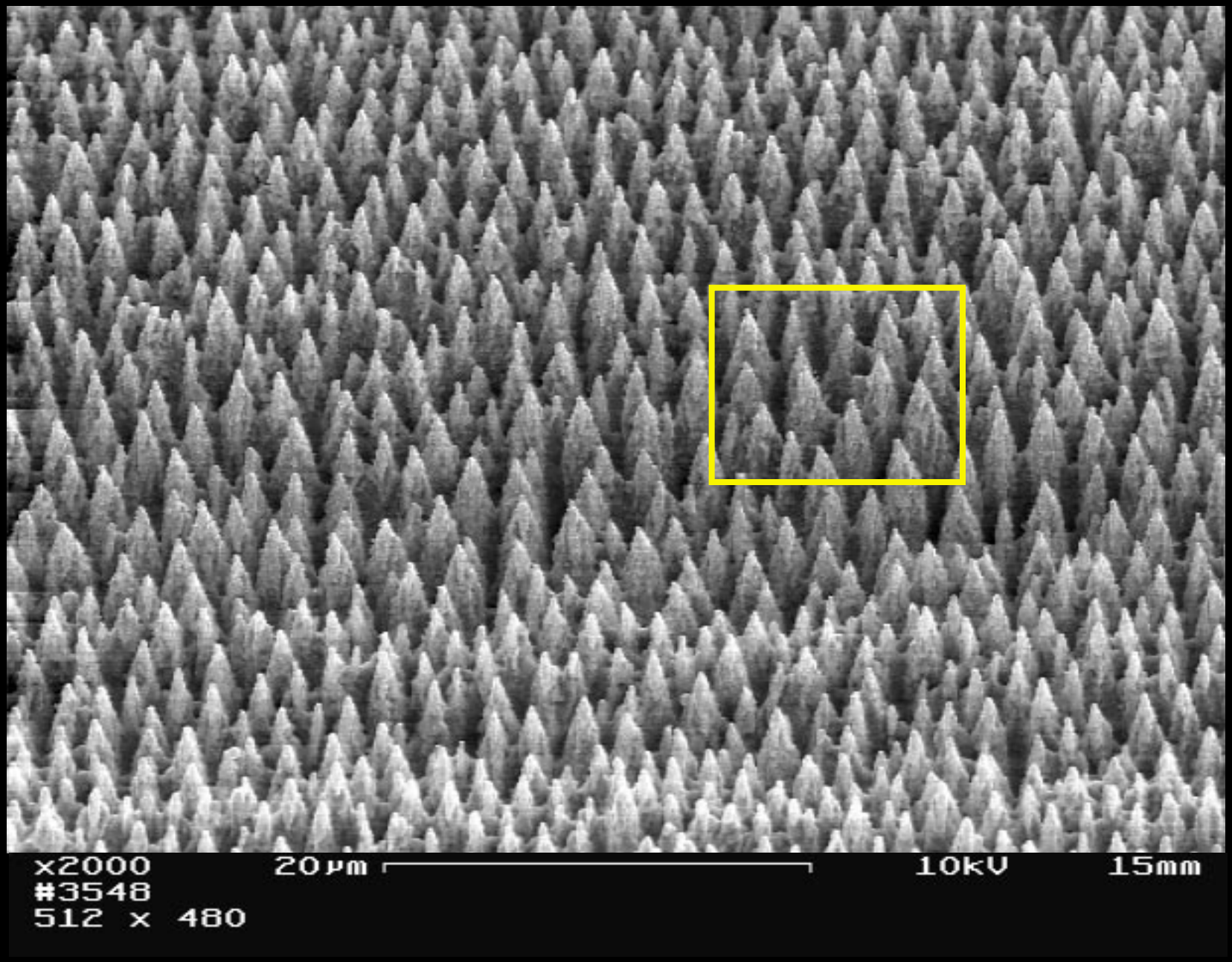
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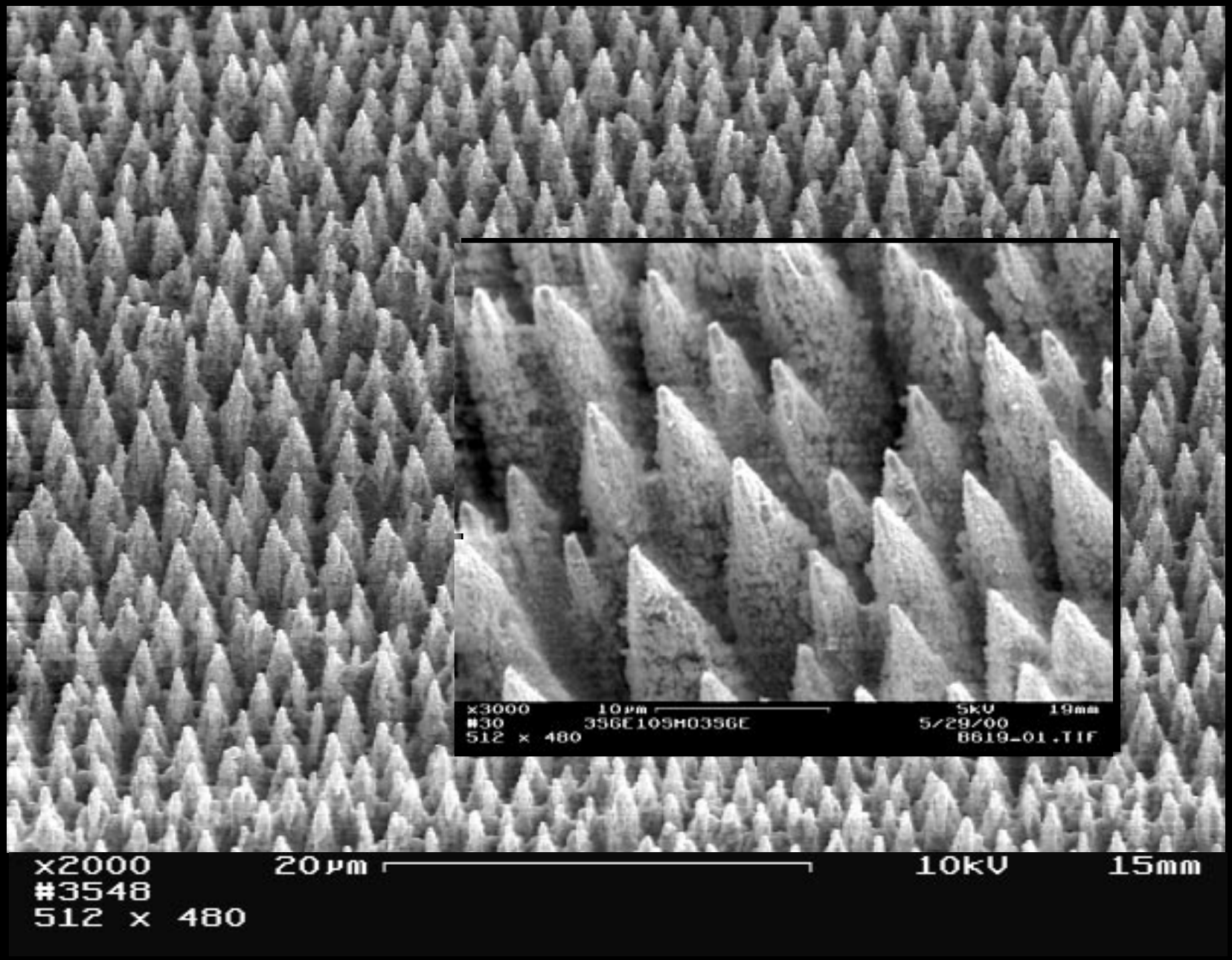
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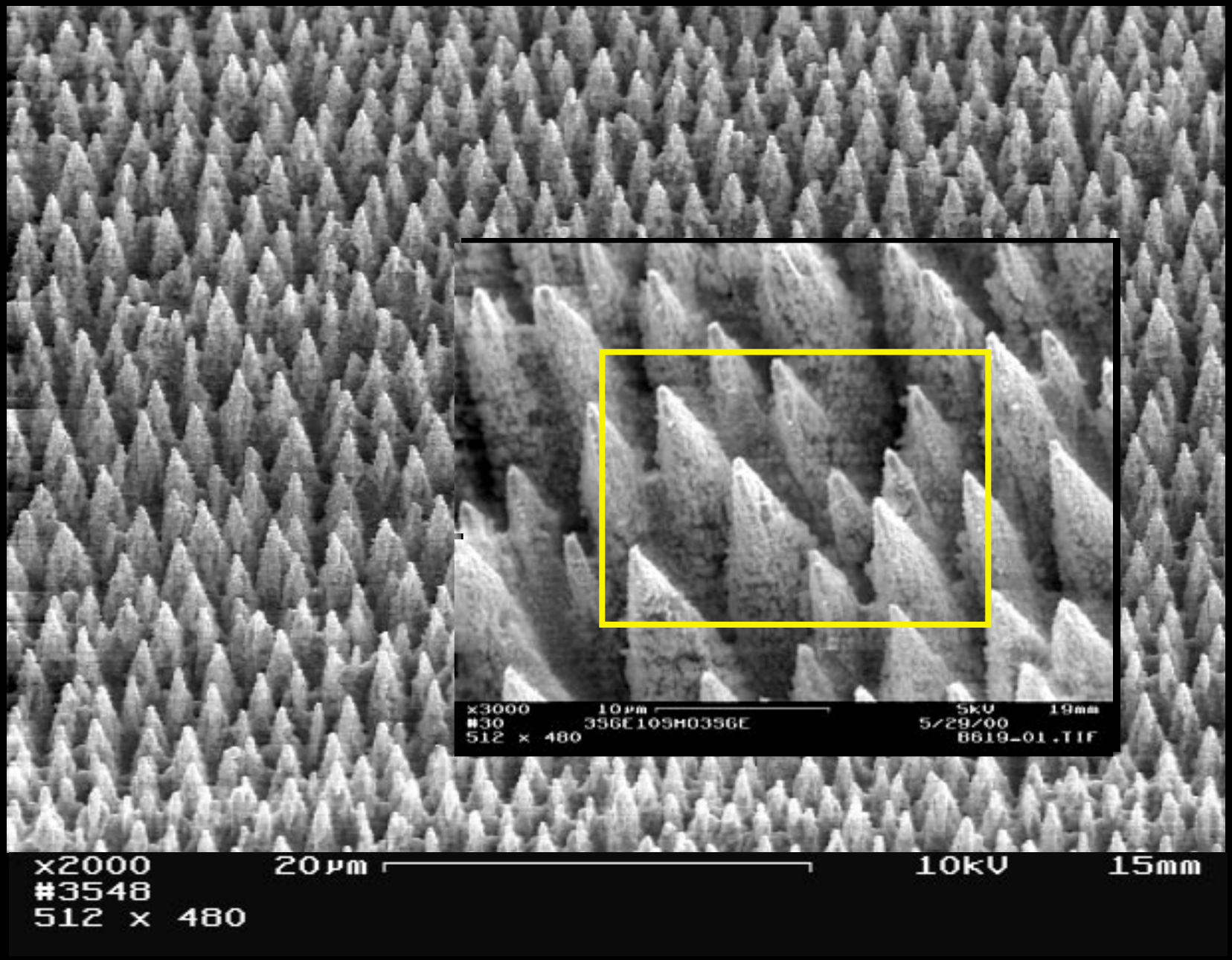
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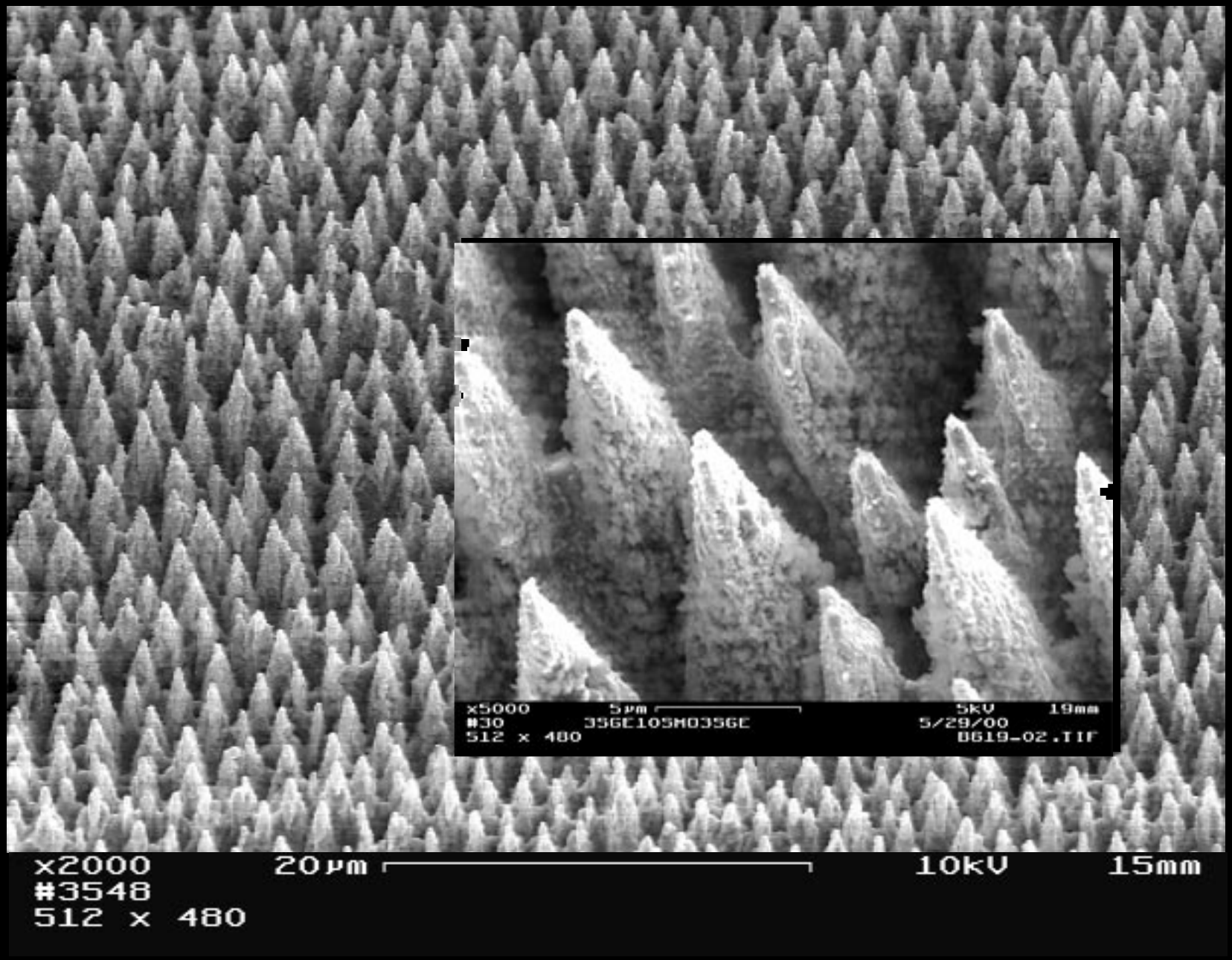
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Outline

Introduction

- fabrication
- optical properties

Field Emission

- background
- **Fowler-Nordheim**

Results

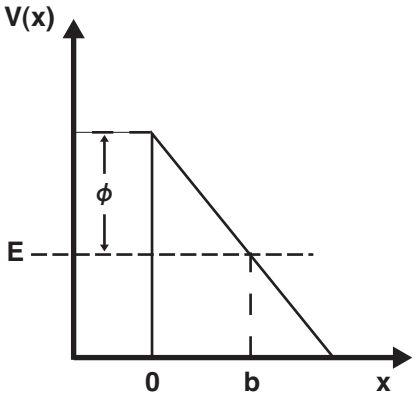
Discussion

Fowler–Nordheim

Time–independent Schrödinger equation

$$\frac{d^2 \psi}{dx^2} + \frac{2m}{\hbar}[V(x) - E]\psi = 0$$

Transmission probability



$$b = \frac{\phi - E}{eF}$$

$$T = \frac{k(b)\,(|\psi(b)|)^2}{k(0)\,(|\psi(0)|)^2}$$

$$k(x) = \frac{\sqrt{2m[V(x) - E]}}{\hbar}$$

Solution to Schrödinger eq. (WKB approximation)

$$\psi(x') = \psi(0)\exp\left(-\int_0^{x'} k(x)\,dx\right)$$

Fowler–Nordheim

Transmission probability with this wavefunction

$$T(E) = \exp\left(-\int_0^b \sqrt{\frac{8\,m}{\hbar^2}\left[V(x) - E\right]}\,dx\right)$$

$$b = \frac{\phi - E}{qF}$$

Integrating

$$T(E) = \exp\left(-\frac{4\sqrt{2\,m}}{3\,\hbar qF}\,(\phi - E)^{3/2}\right)$$

Fowler–Nordheim

The supply function N(E)dE

$$N(E)\,dE = \frac{4\pi m k_b T}{h^3} \ln\left(1 + \exp\left(-\frac{E-\mu}{k_b T}\right)\right) dE$$

Calculate the total current density j

$$j = \int_0^\infty eN(E)\,T(E)\,dE$$

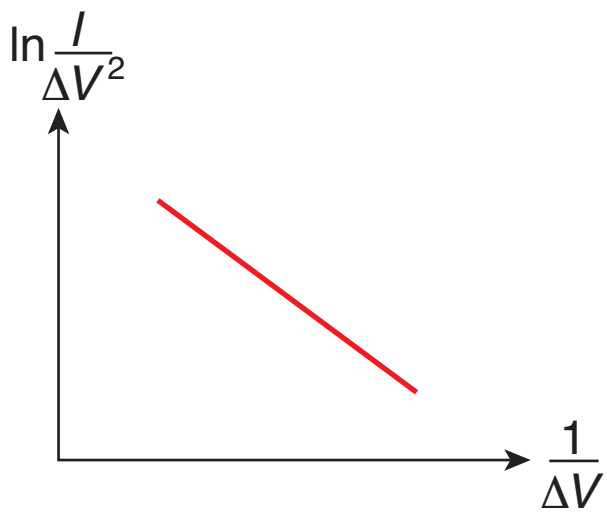
$$j = \frac{e^3 F^2}{8\pi h\phi} \frac{m_e}{m} \exp\left(-\frac{4\sqrt{2m}\,\phi^{3/2}}{3\hbar eF}\right)$$

Substituting in I = Aj and F = βV

$$I = \frac{Ae^3(\beta V)^2}{8\pi h\phi} \frac{m_e}{m} \exp\left(-\frac{4\sqrt{2m}\,\phi^{3/2}}{3\hbar e\beta V}\right)$$

Fowler–Nordheim

$$\ln(I/\Delta V^2) = \ln a - b(1/\Delta V)$$



R.H. Fowler and L. Nordheim, Proc. R. Soc. Lond. A (1928)

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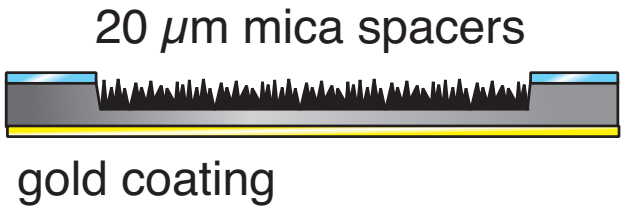
Field emission setup

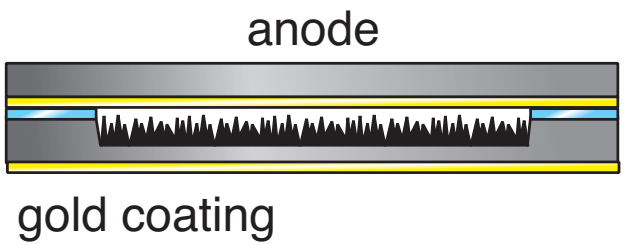
Field emission setup

gold coating

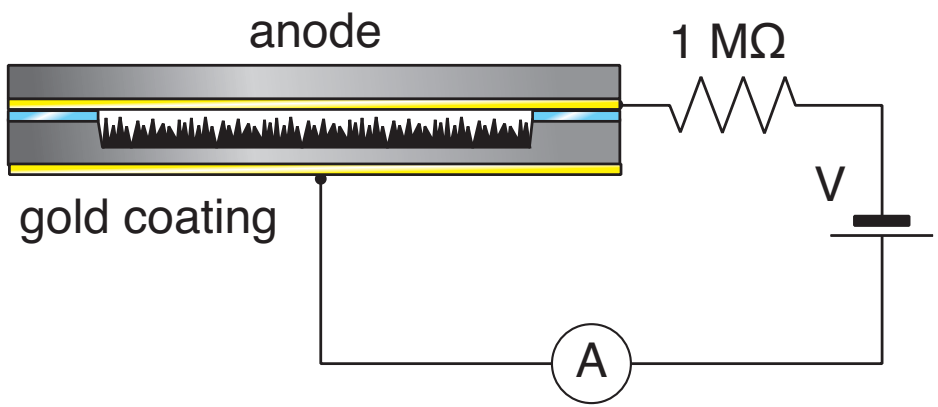
Field emission setup



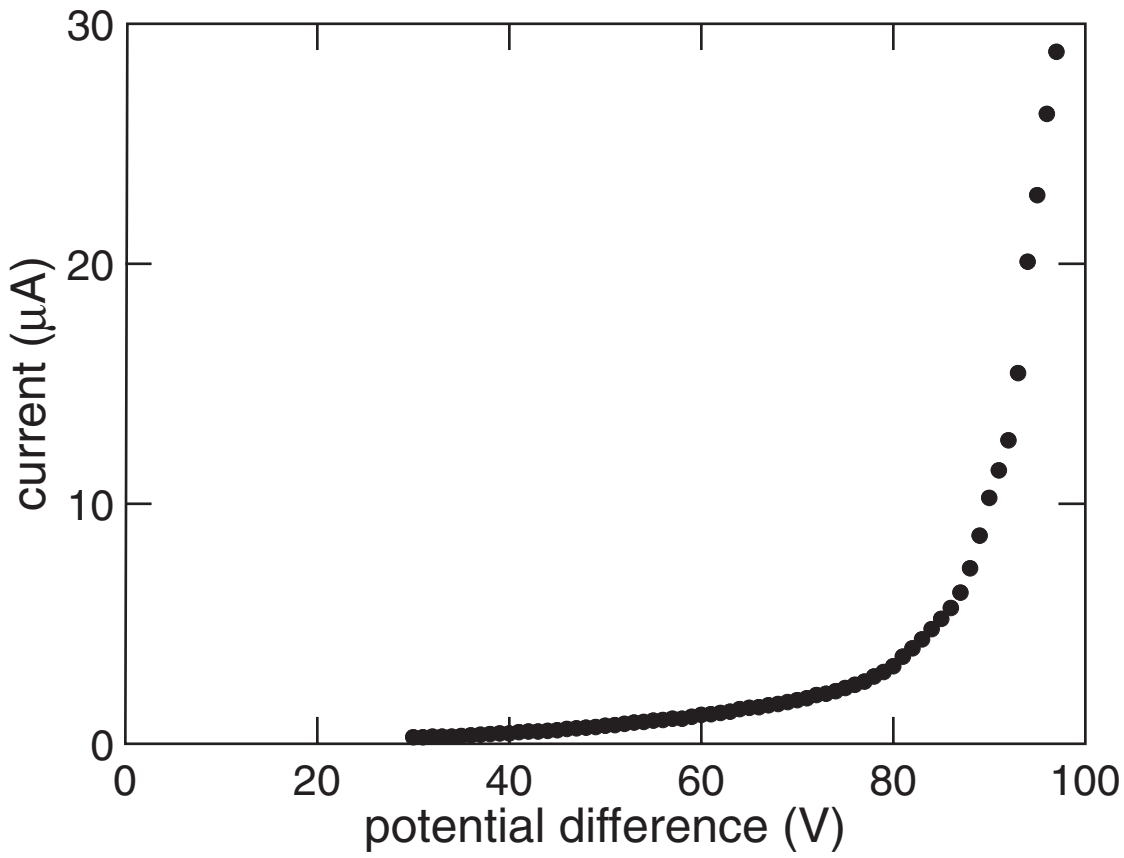
Field emission setup



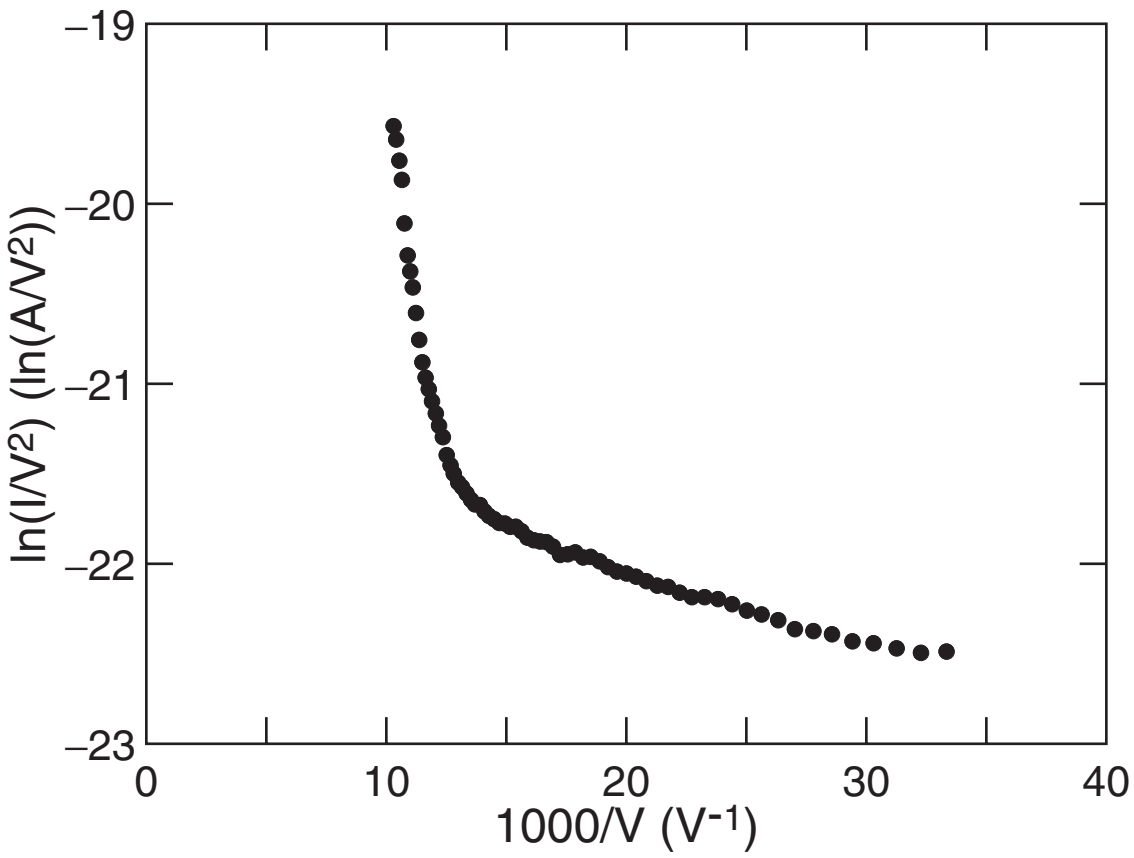
Field emission setup



I–V Characteristics



Fowler–Nordheim plot

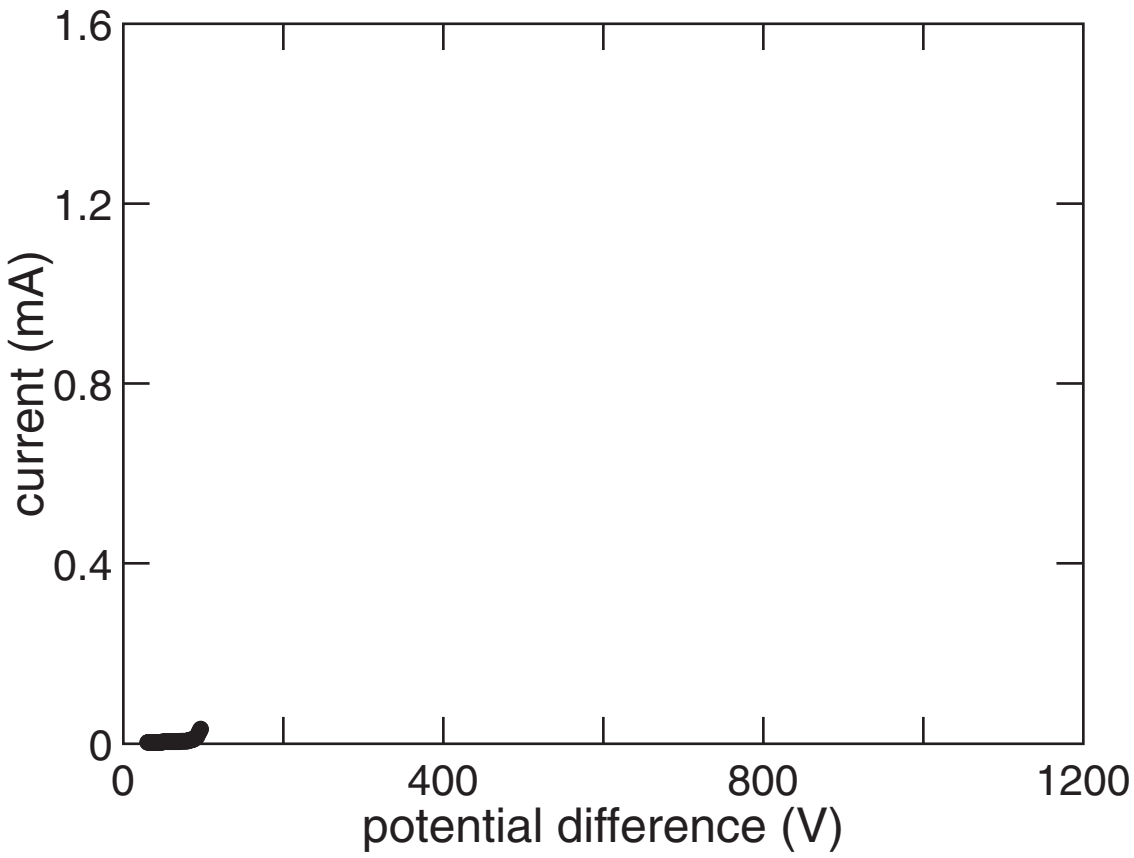


Results

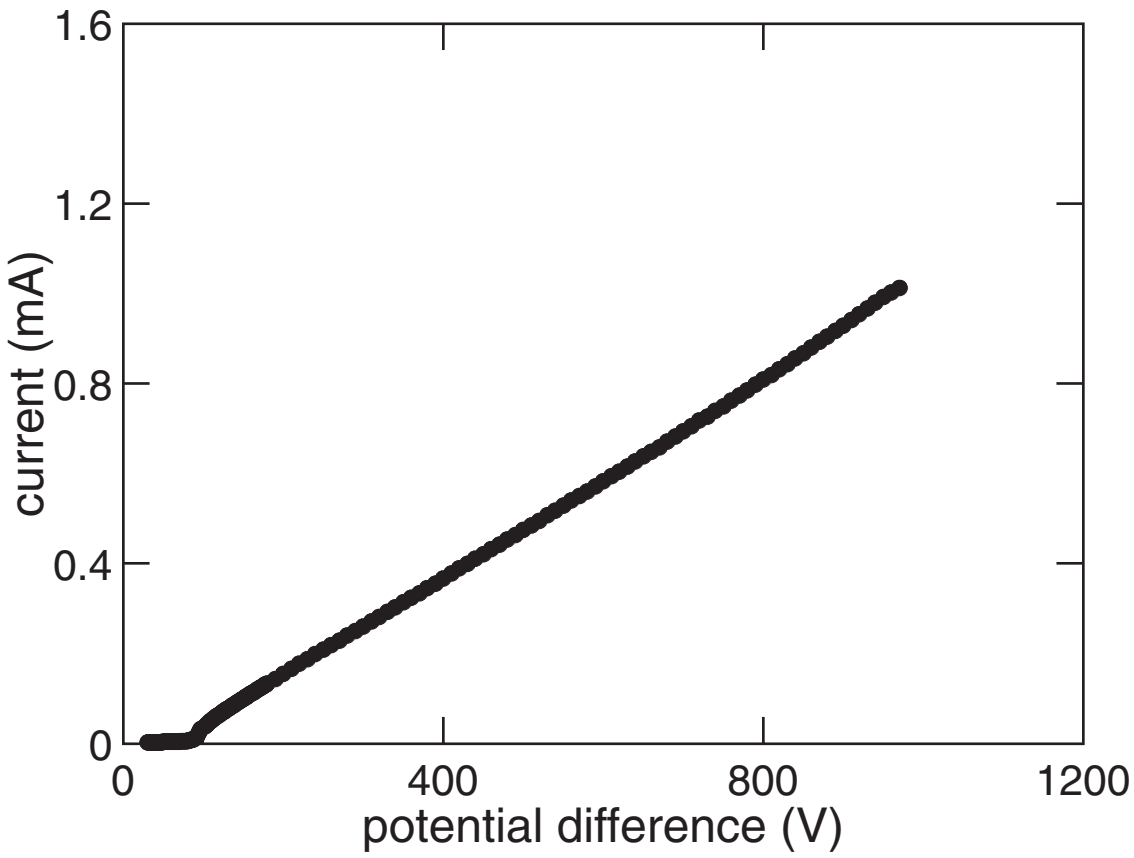
Emission properties

- **turn-on field (1 $\mu A/cm^2$): 1.3 V/μm**
- **threshold field (10 $\mu A/cm^2$): 2.15 V/μm**

I–V Characteristics



I–V Characteristics



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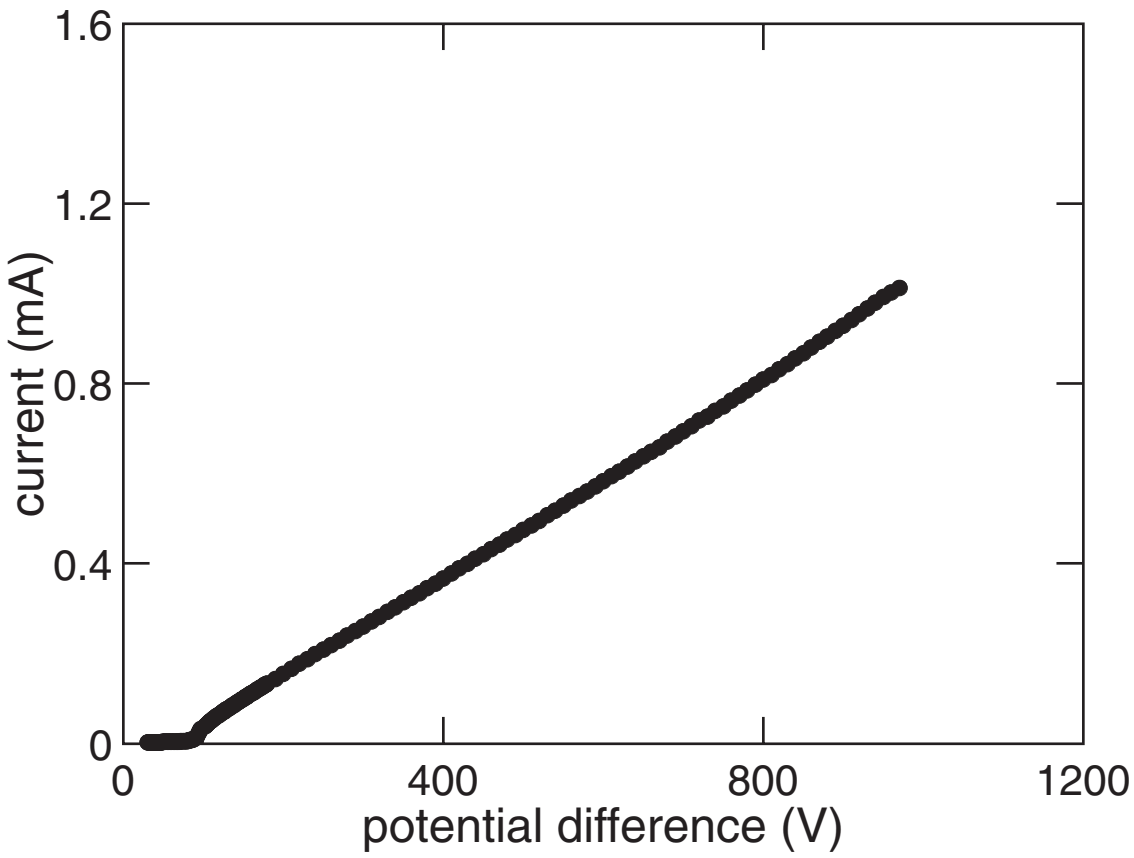
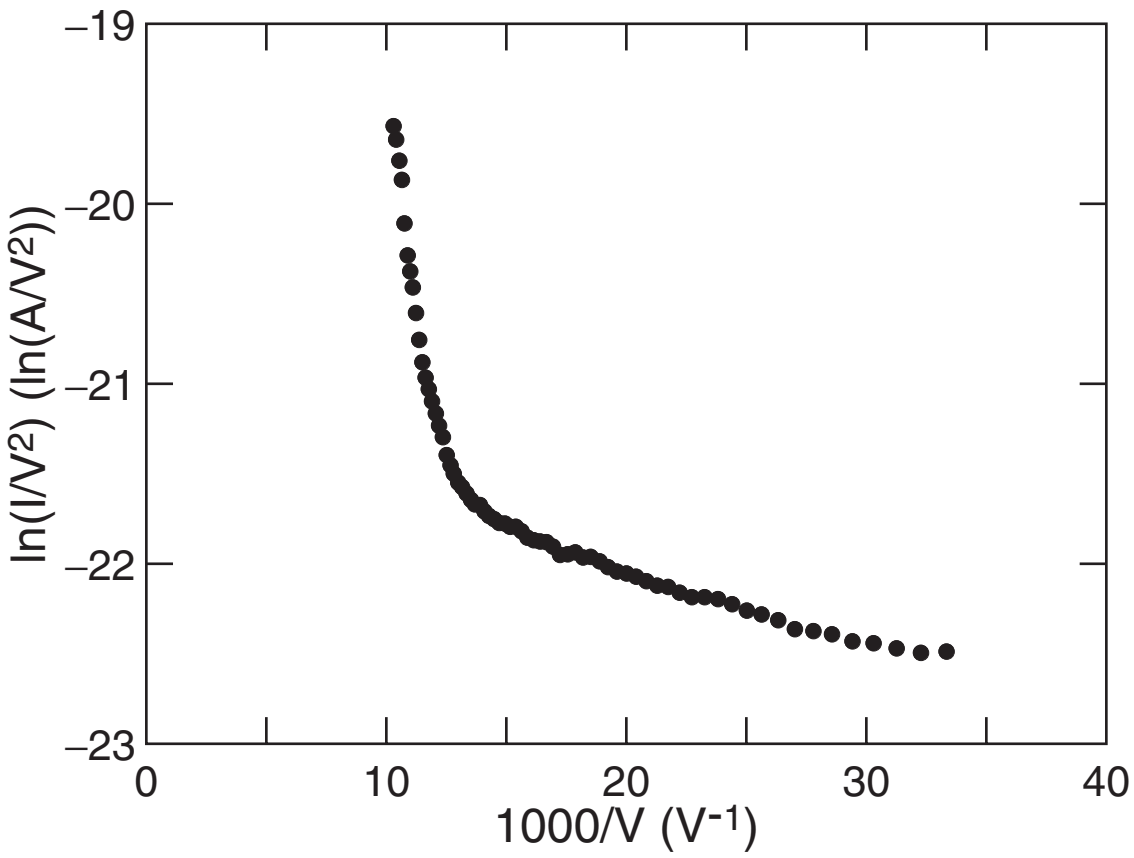
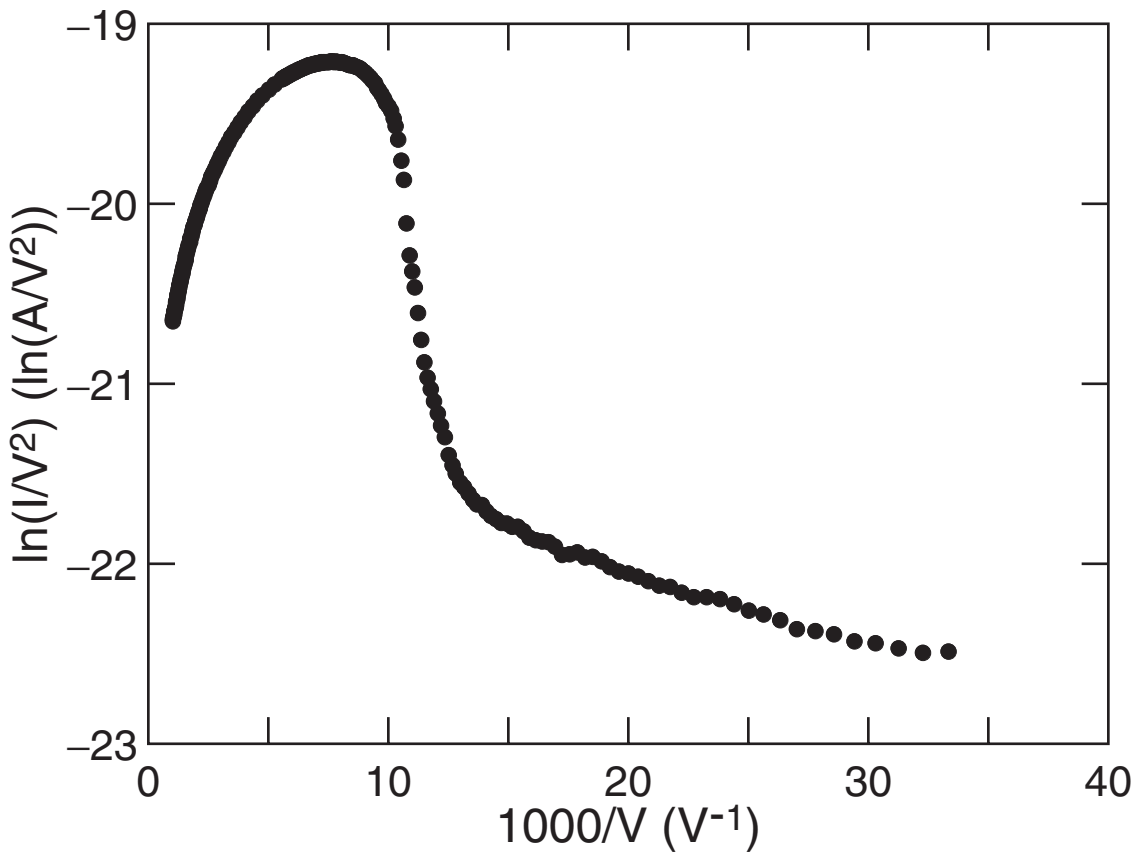


maximum current: 2 mA (4 mm^2 sample)

Fowler–Nordheim plot



Fowler–Nordheim plot



Outline

Introduction

- fabrication
- optical properties

Field Emission

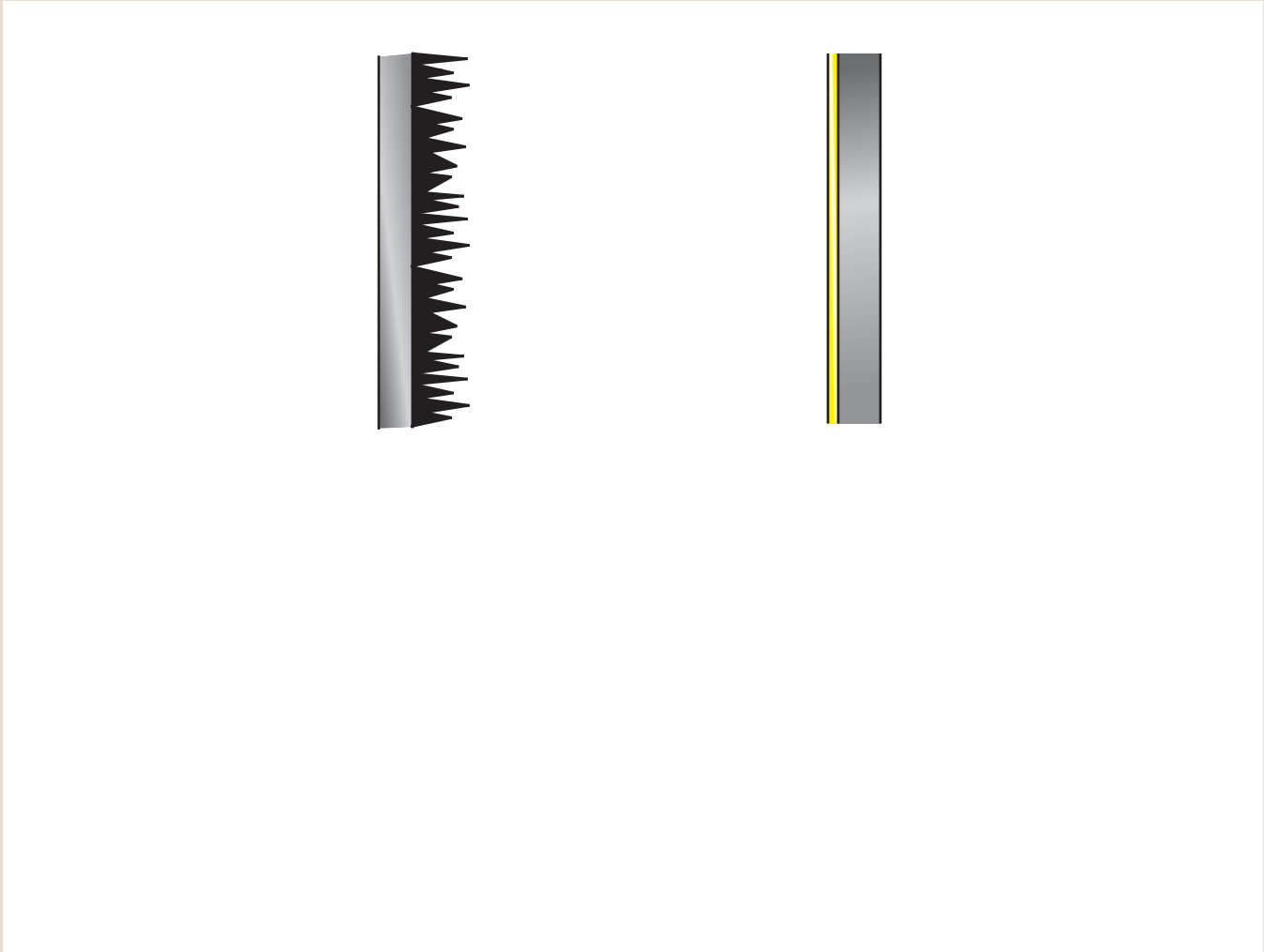
- background
- Fowler-Nordheim

Results

Discussion

Discussion

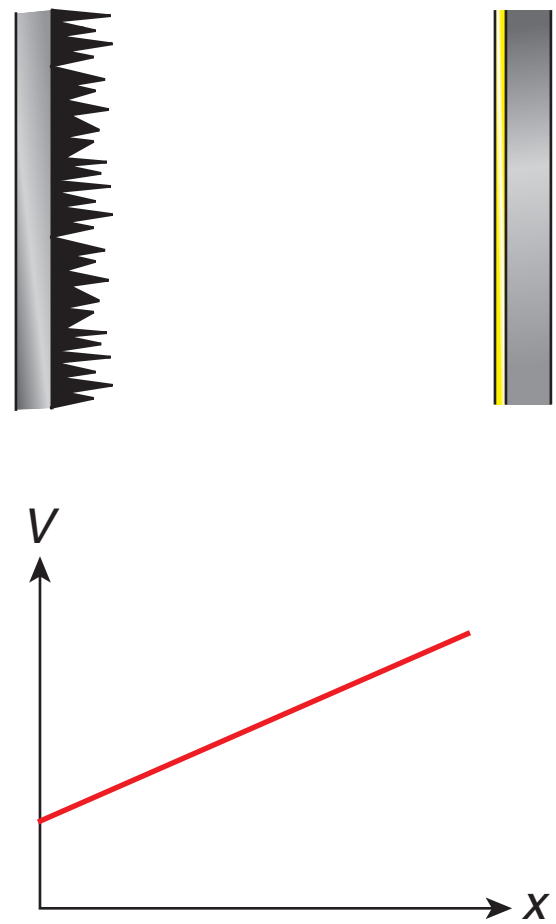
space charge effect



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Discussion

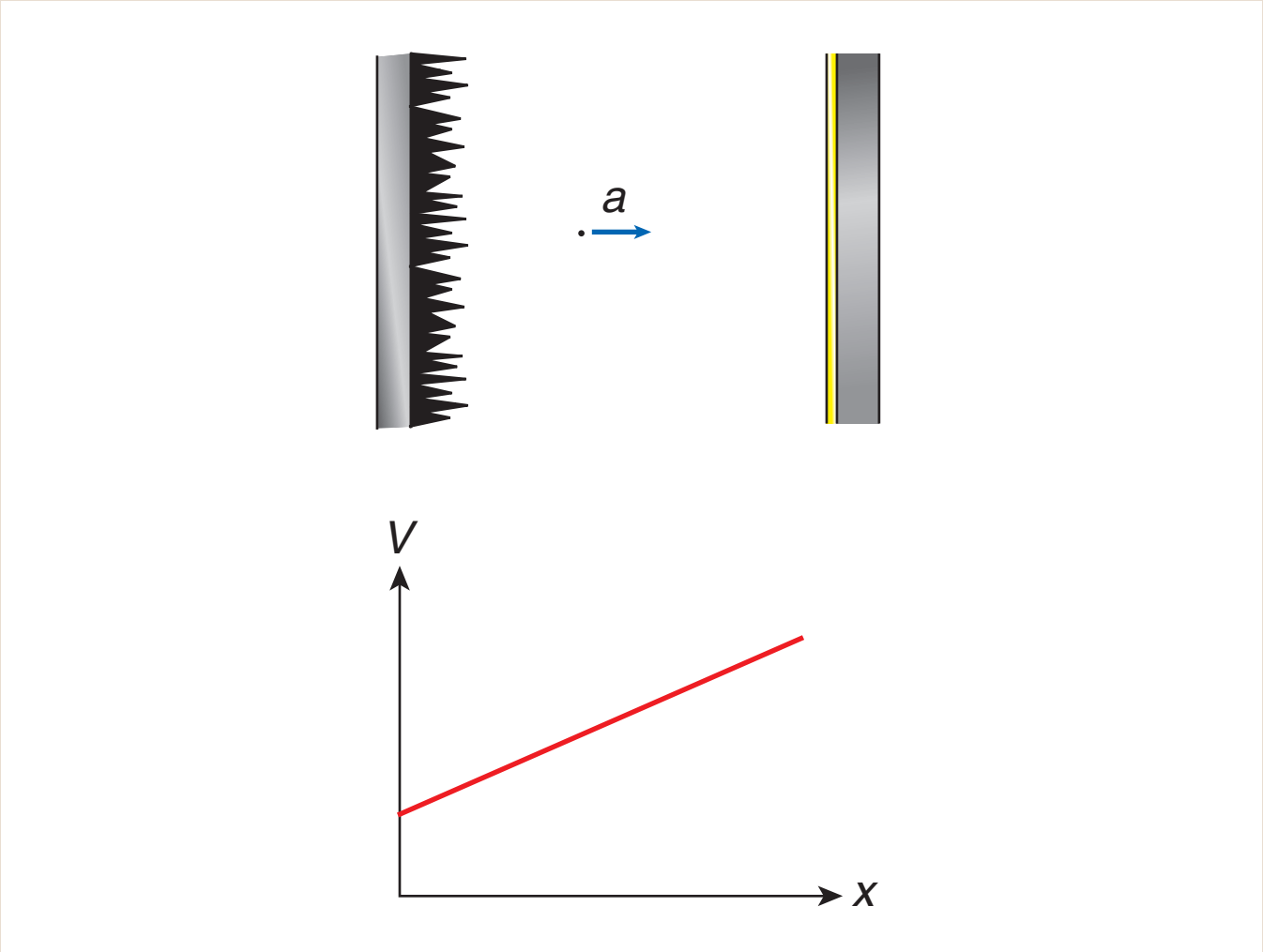
space charge effect



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Discussion

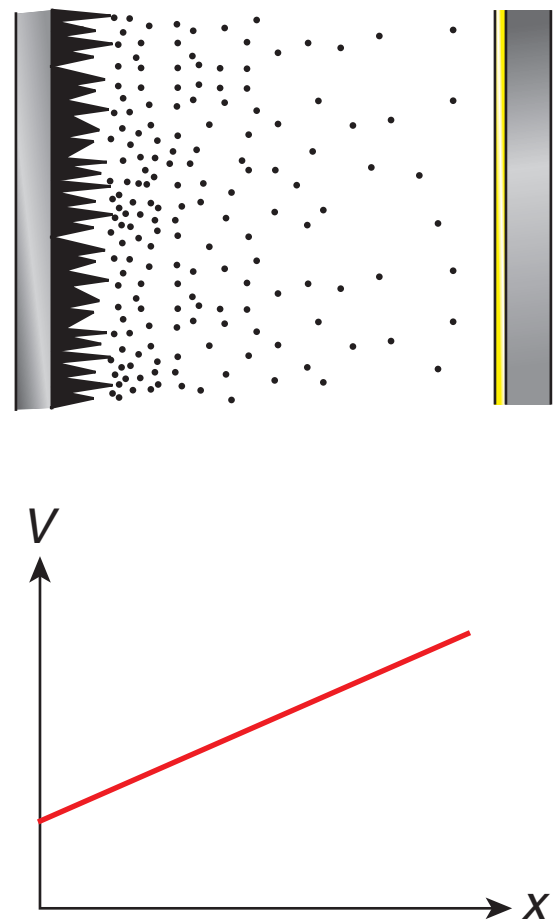
space charge effect



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Discussion

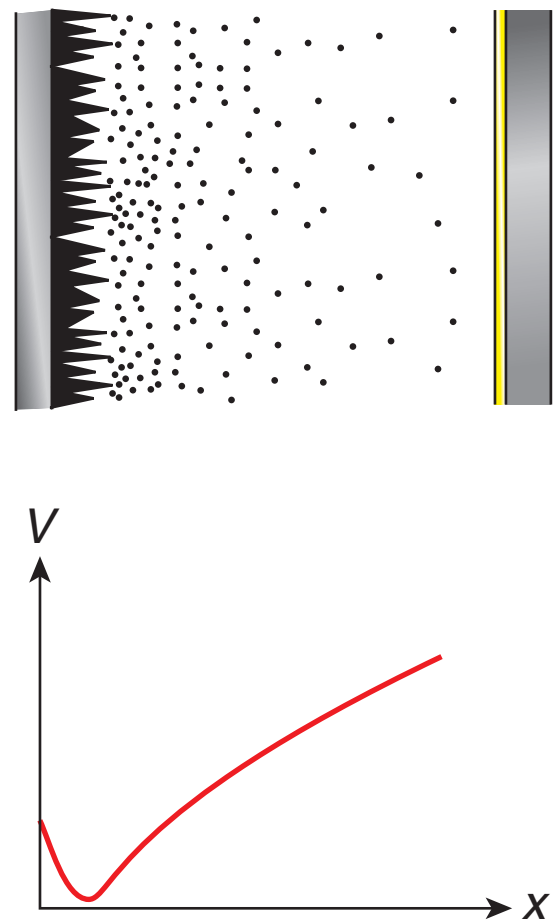
space charge effect



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

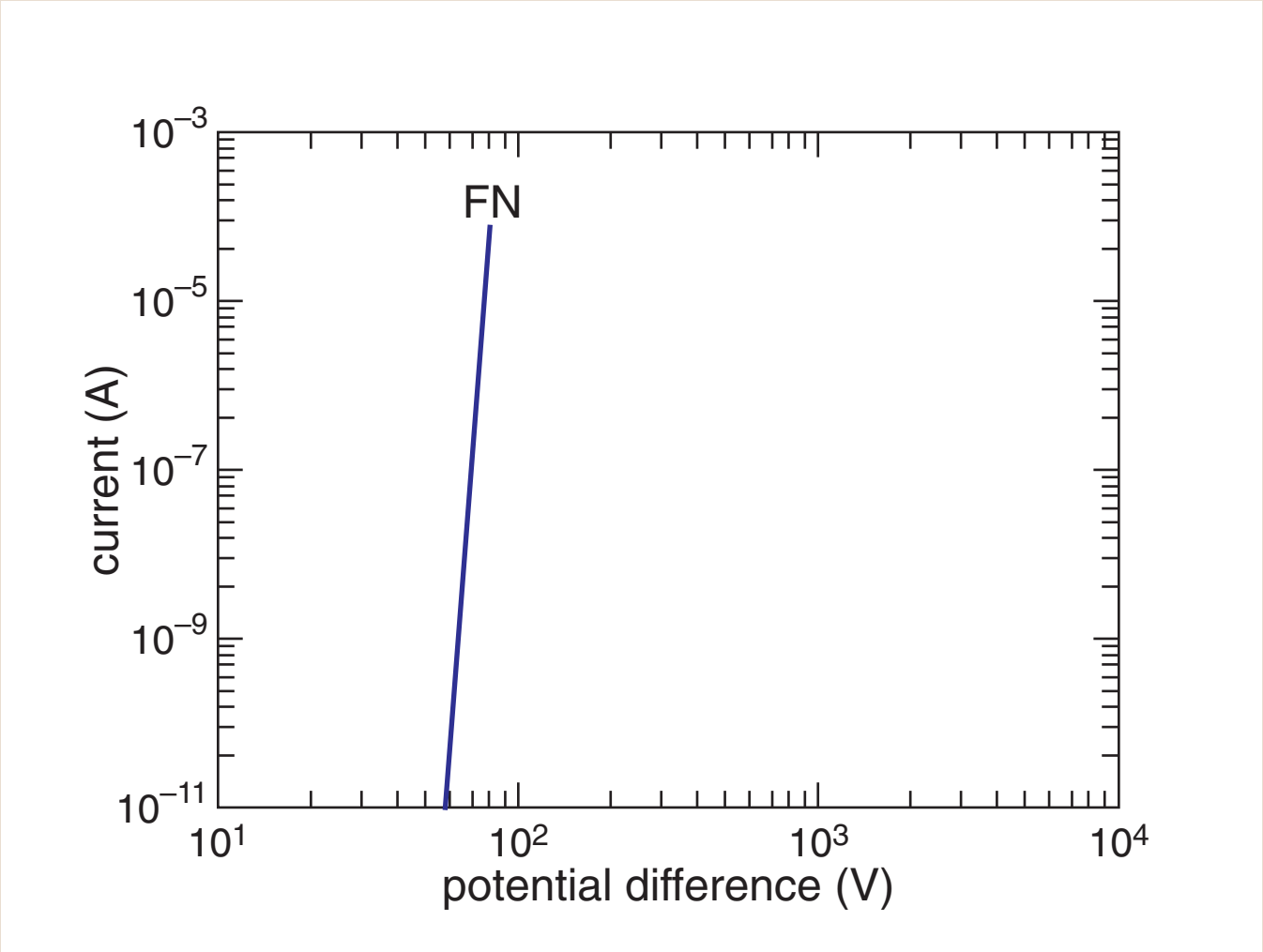
Discussion

space charge effect



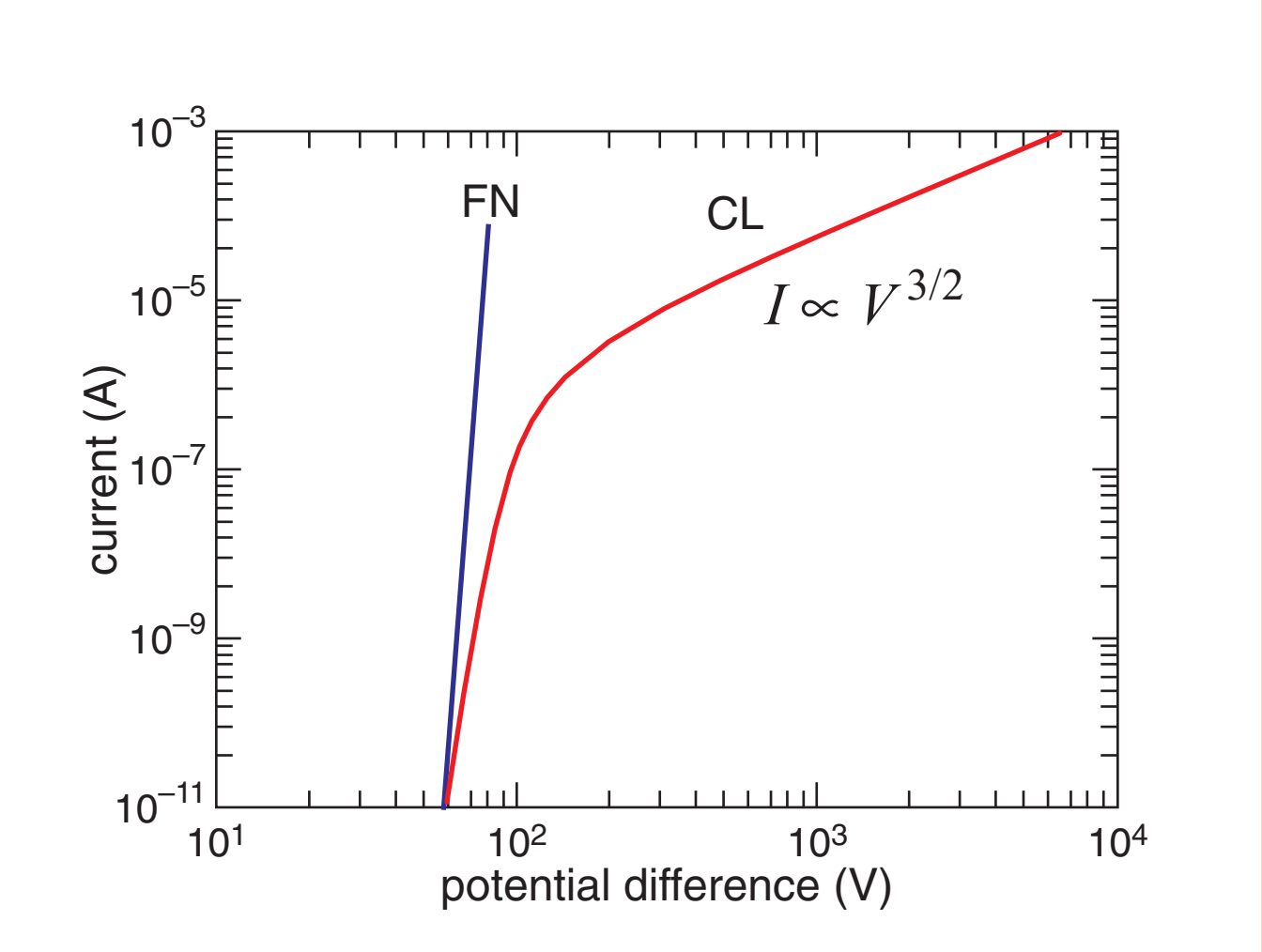
Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Fowler–Nordheim to Child–Langmuir



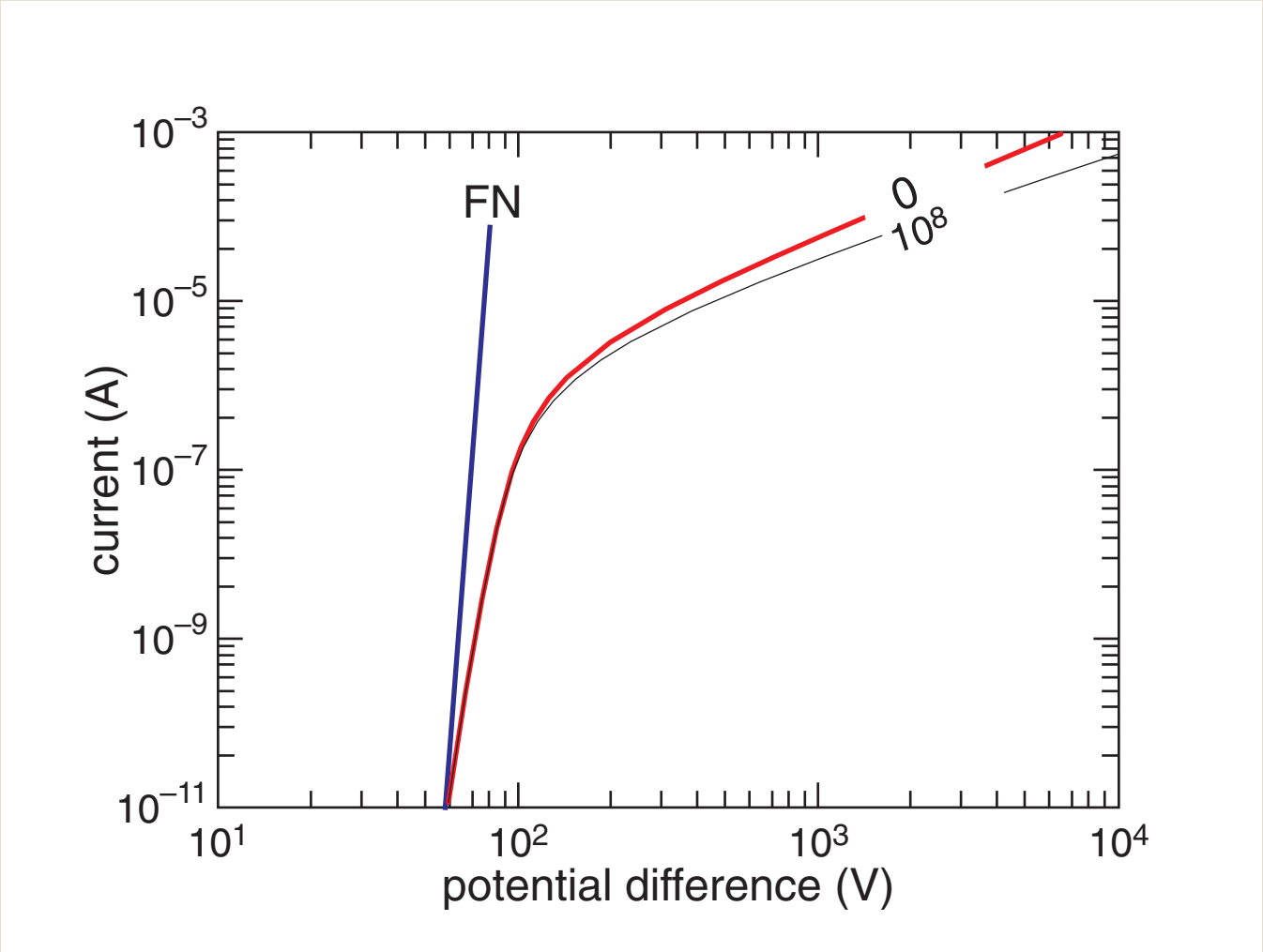
Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Fowler–Nordheim to Child–Langmuir



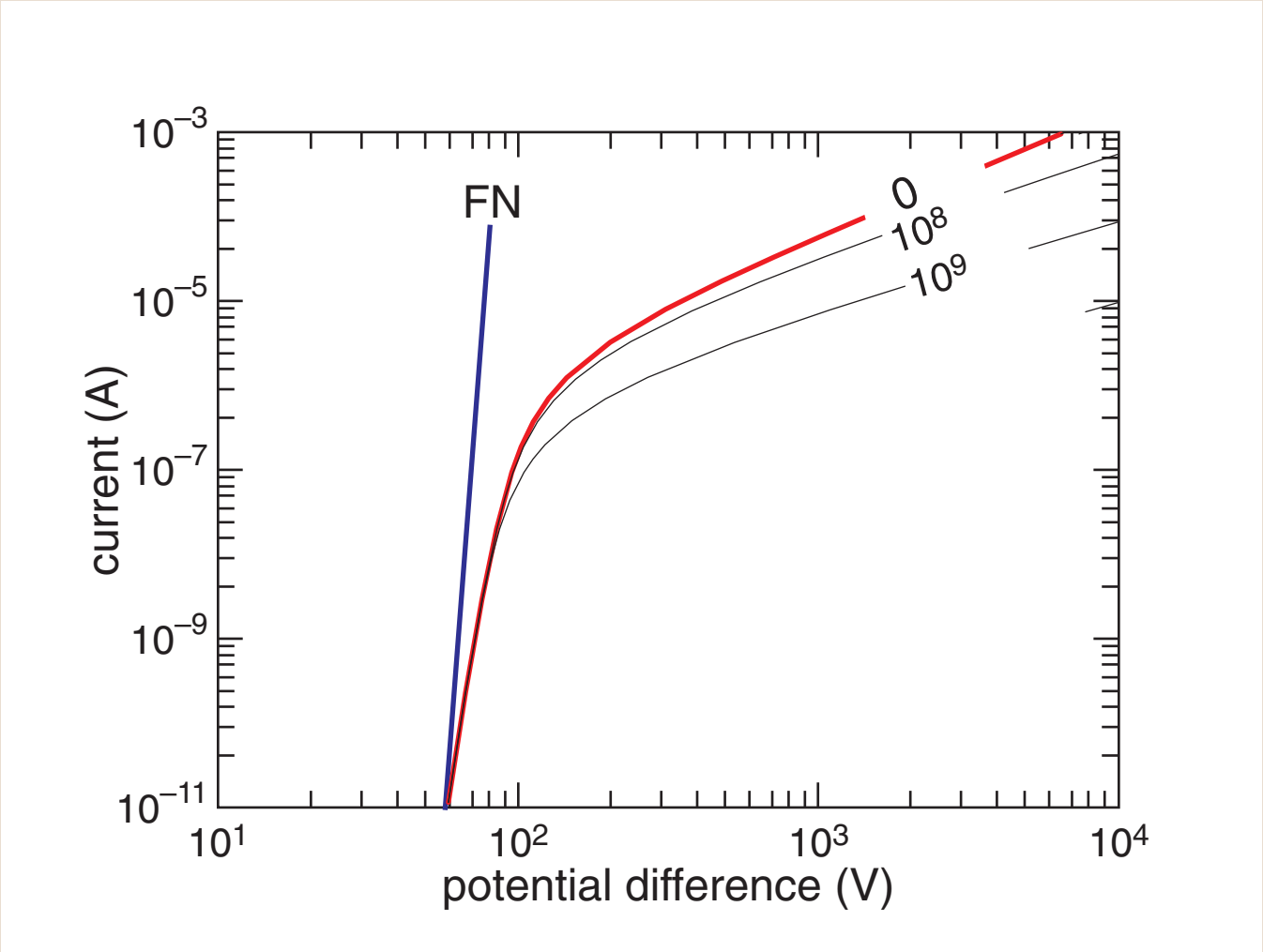
Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Fowler–Nordheim to Child–Langmuir



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Fowler–Nordheim to Child–Langmuir



Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

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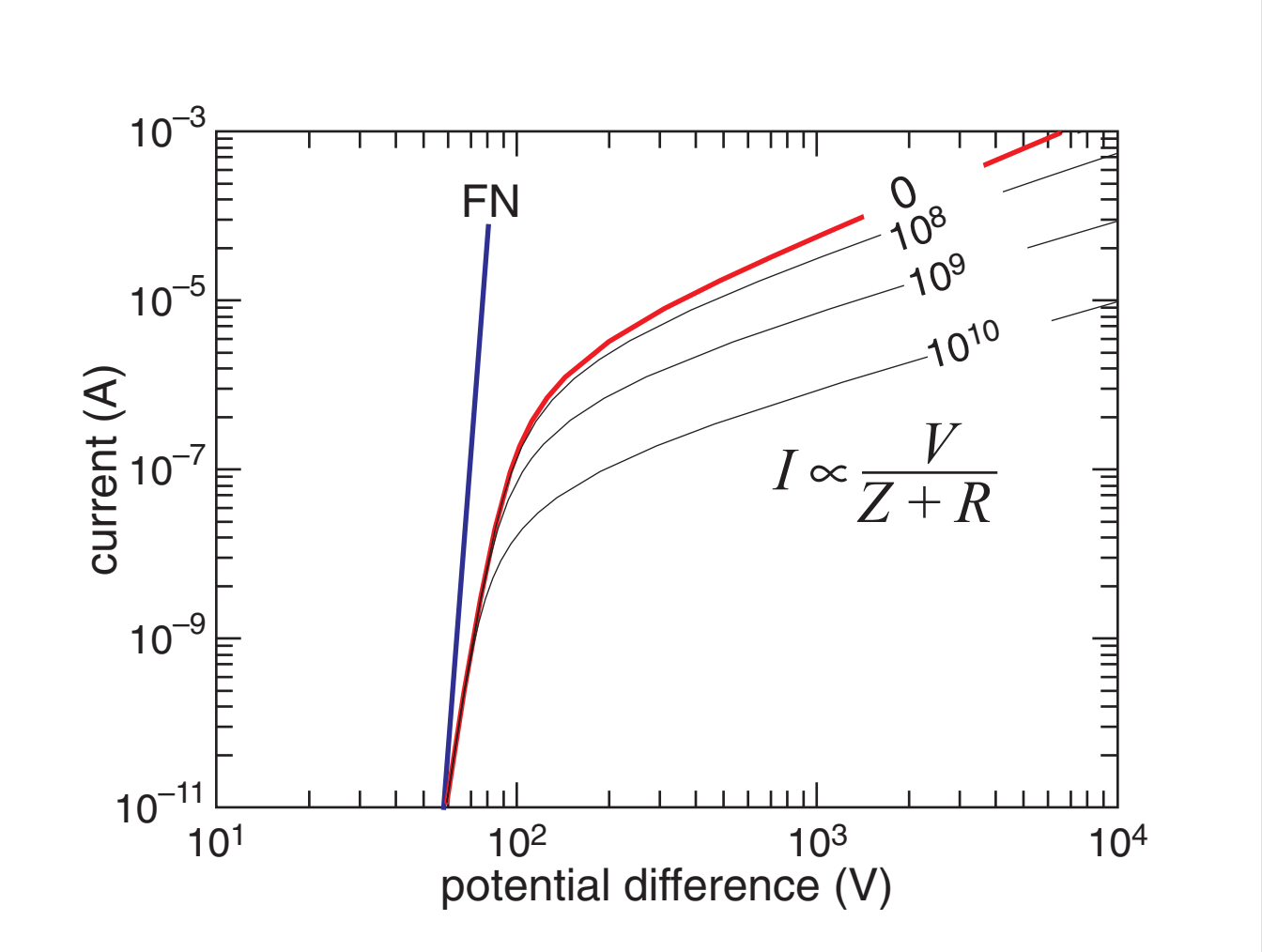


Y.Y. Lau et al., Phys. Plasmas 1, 2082 (1994)

Discussion

Ion channeling and Rutherford backscattering

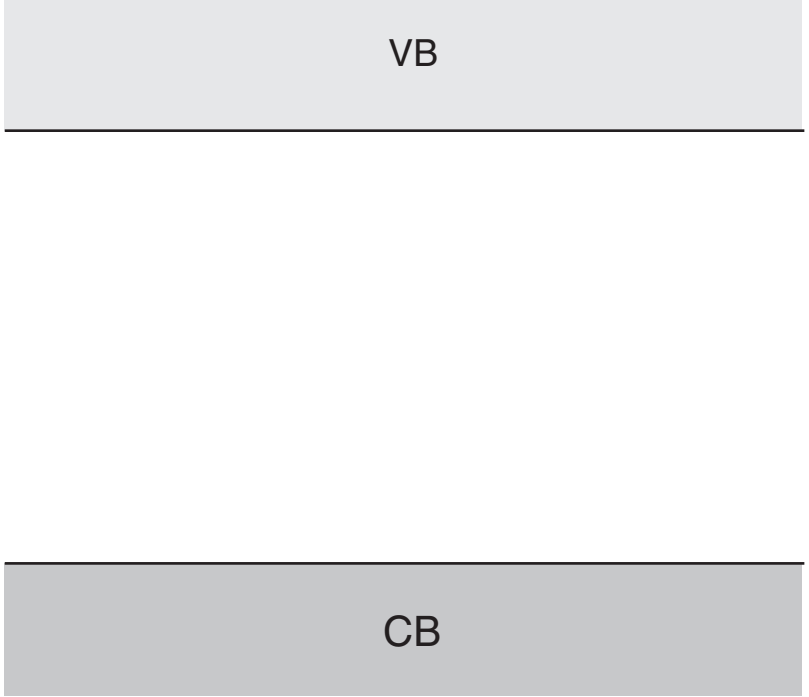
- **surface retains crystalline order**
- **high density of defects**

Discussion

Secondary ion mass spectrometry (SIMS):

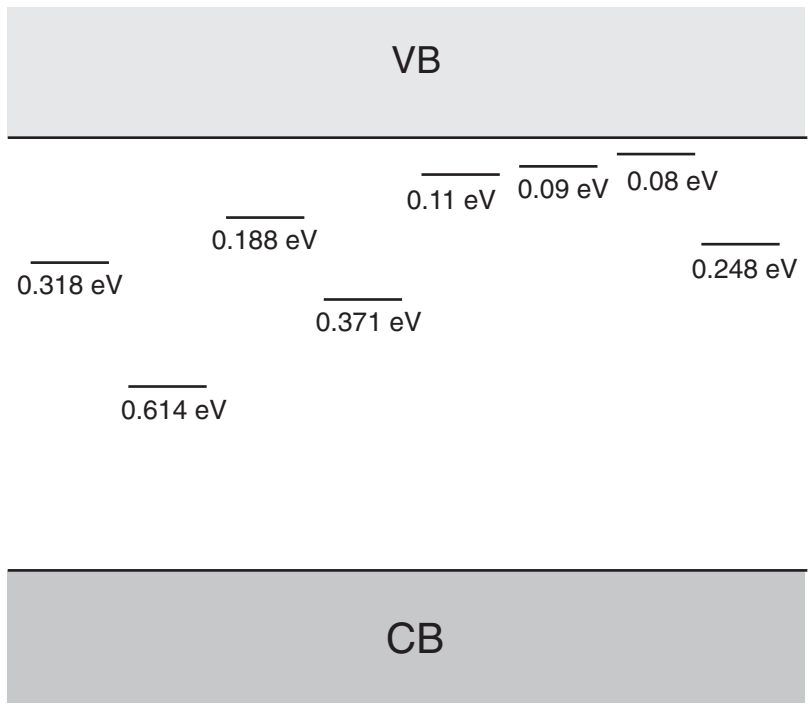
- 10^{20} cm^{-3} sulfur
- 10^{17} cm^{-3} fluorine

Discussion



Discussion

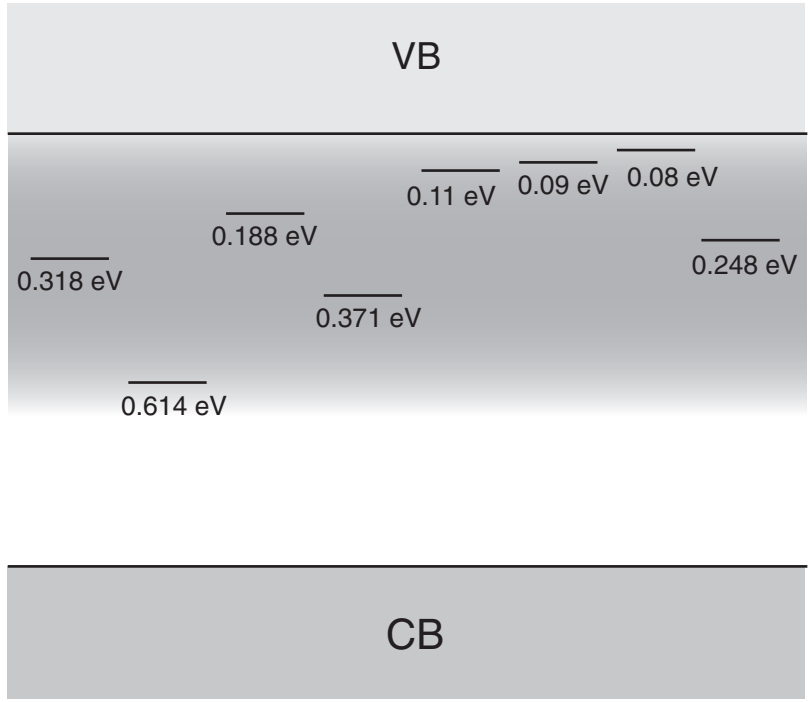
sulfur introduces states into the gap



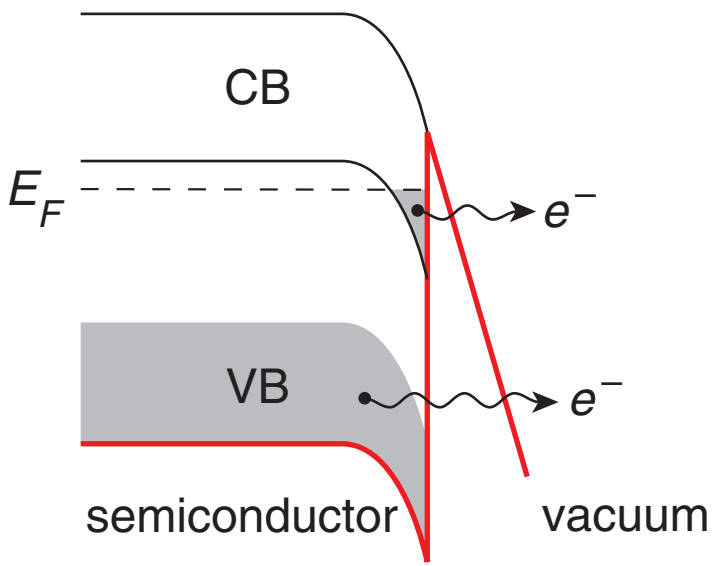
Janzén, et al., Phys. Rev. B 29,1907 (1984)

Discussion

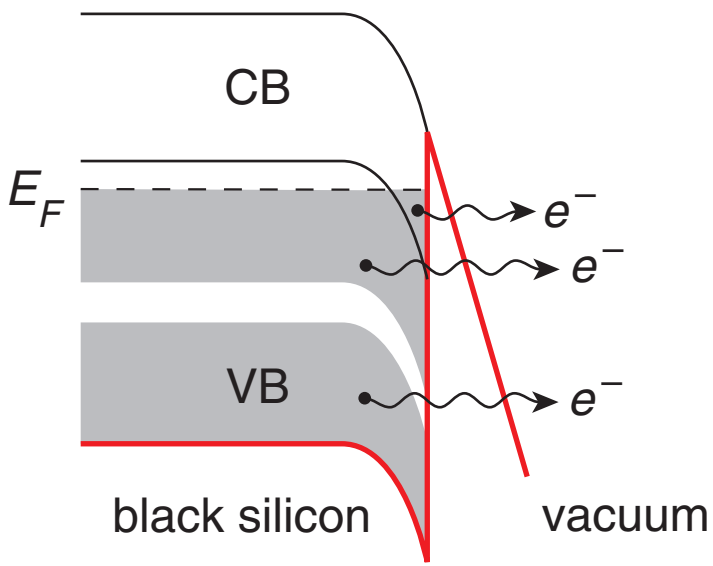
sulfur introduces states into the gap



Discussion



Discussion

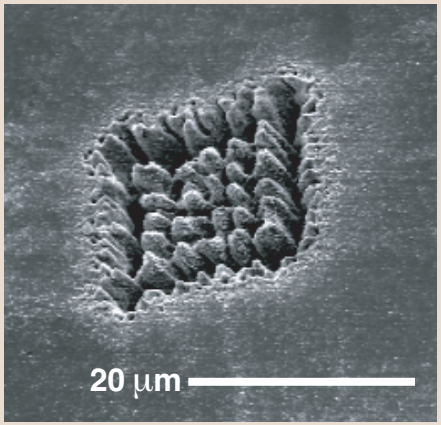


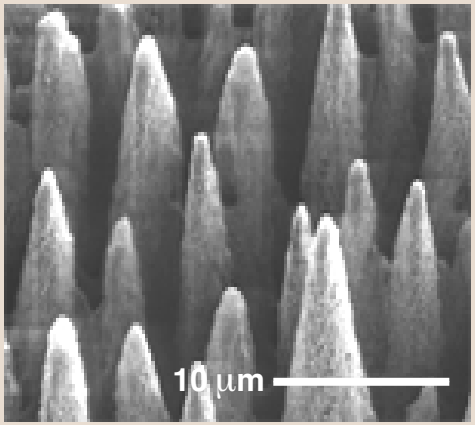
Conclusions

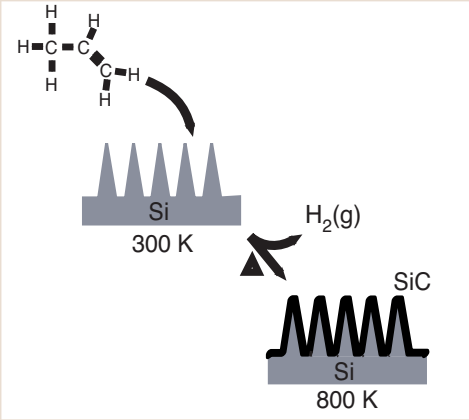
Micron-sized conical field-emitters

- fabricated by simple, maskless process
- can be integrated with microelectronics
- provides stable, high field-emission current
- are durable

Future directions







- Ordered arrays
- Other gases
- Functionalizing
- Electron energy and band structure studies

Acknowledgements

Rebecca Younkin, Mike Sheehy, Catherine Crouch, Josh Levinson, and the Mazur group

Li Zhao, Fudan University, Shanghai, China

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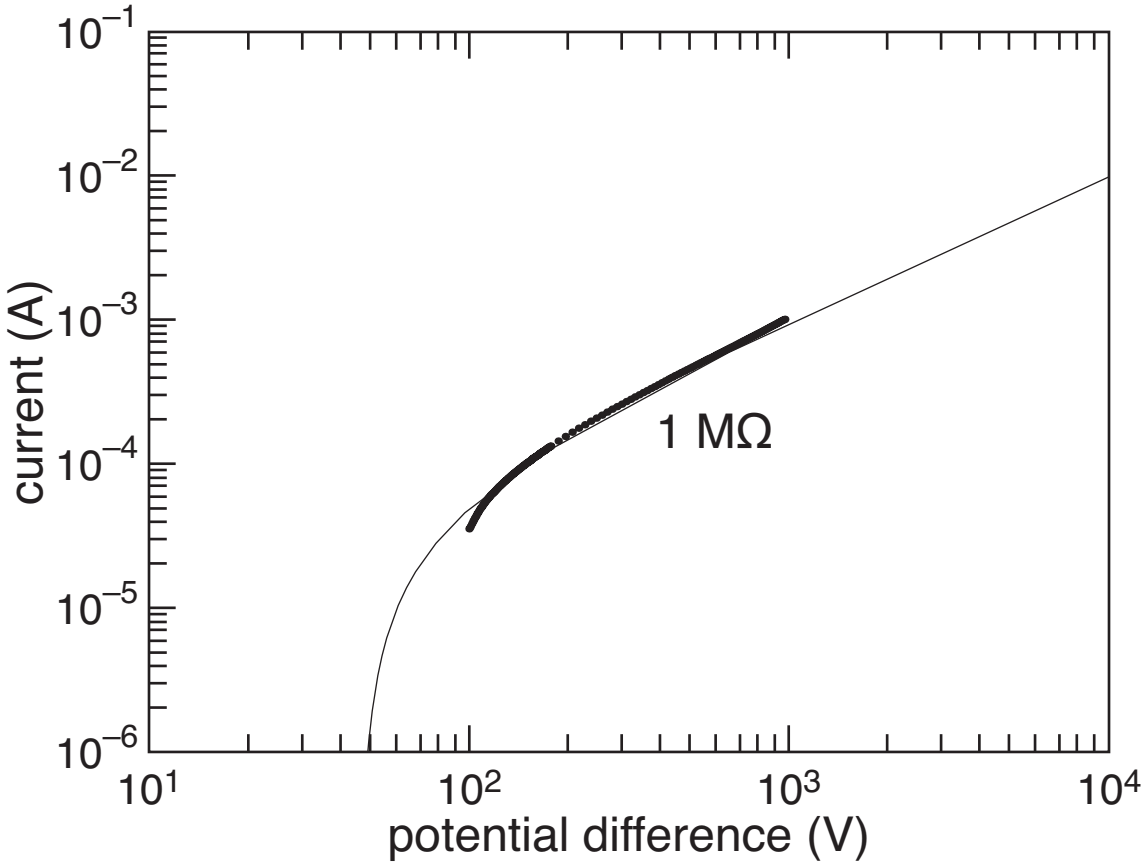
Fowler–Nordheim to Child–Langmuir



Fowler–Nordheim to Child–Langmuir