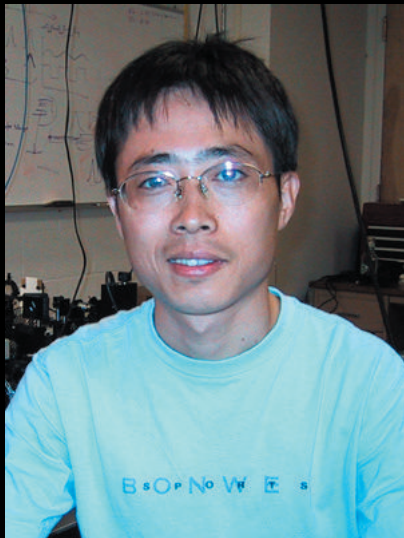


Wrapping light around a hair



SPS/DSP Lunch Talk
University of Kentucky
Kentucky, KY, 25 October 2007





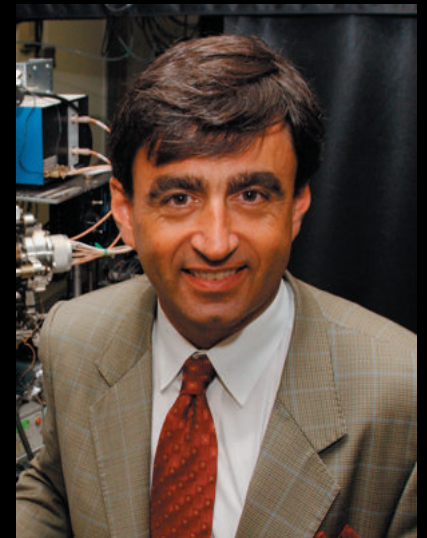
Limin Tong



Rafael Gattass



Geoff Svacha



Eric Mazur

and also....

at Harvard:

Jonathan Aschom

Mengyan Shen

Iva Maxwell

James Carey

Brian Tull

Dr. Yuan Lu

Dr. Richard Schalek

Prof. Federico Capasso

Prof. Cynthia Friend

at Zhejiang University:

Dr. Sailing He

Dr. Jingyi Lou

Xuwen Chen

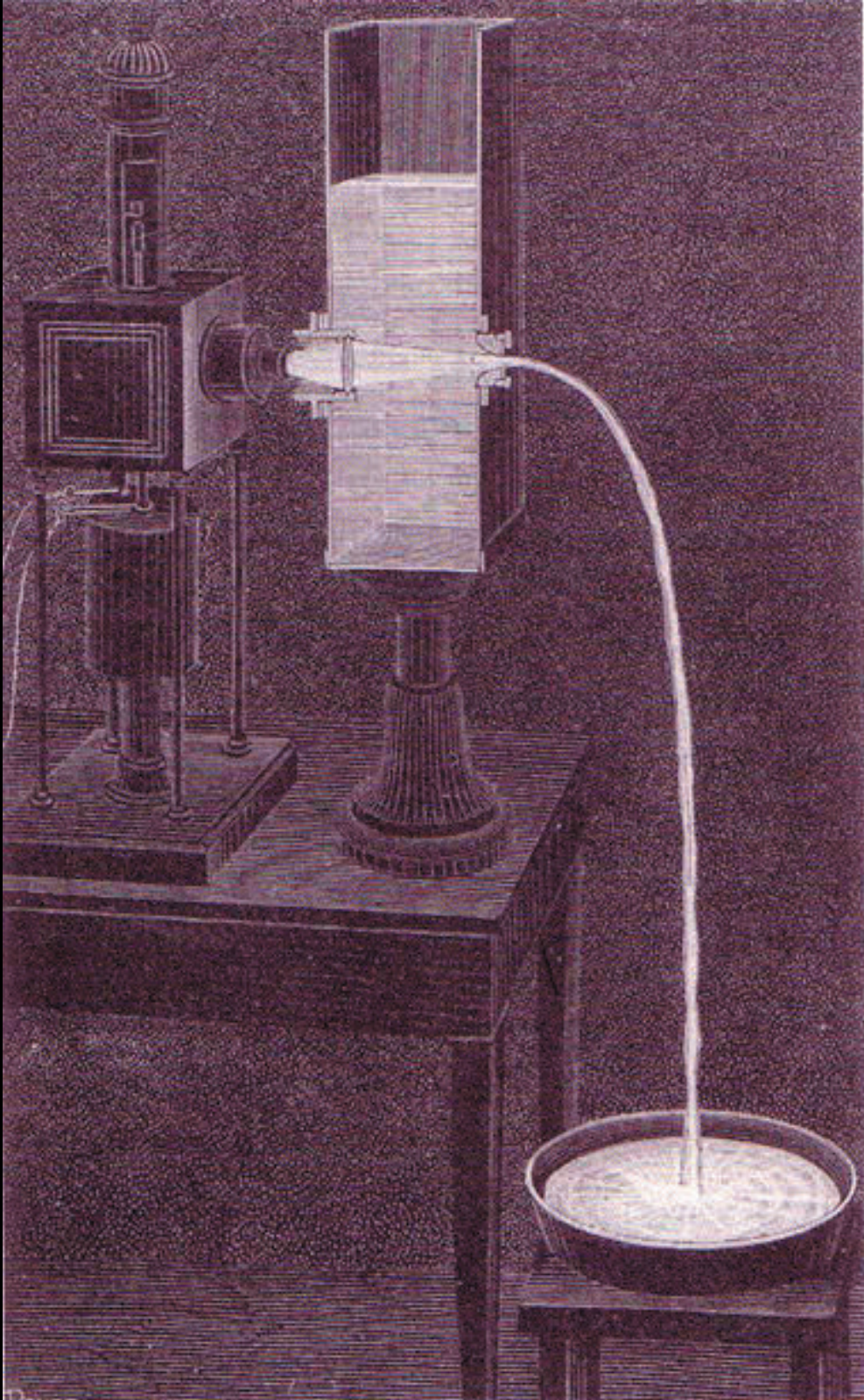
Liu Liu

Zhanghua Han

Dr. Ray Mariella (LLNL)

“I managed to illuminate the interior of a stream in a dark space. I have discovered that this strange arrangement offers one of the most beautiful, and most curious experiments that one can perform in a course on Optics.”

Daniel Colladon, *Comptes Rendus*, 15, 800–802 (1842)



D. Colladon, *La Nature*, 325 (1884)



W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.

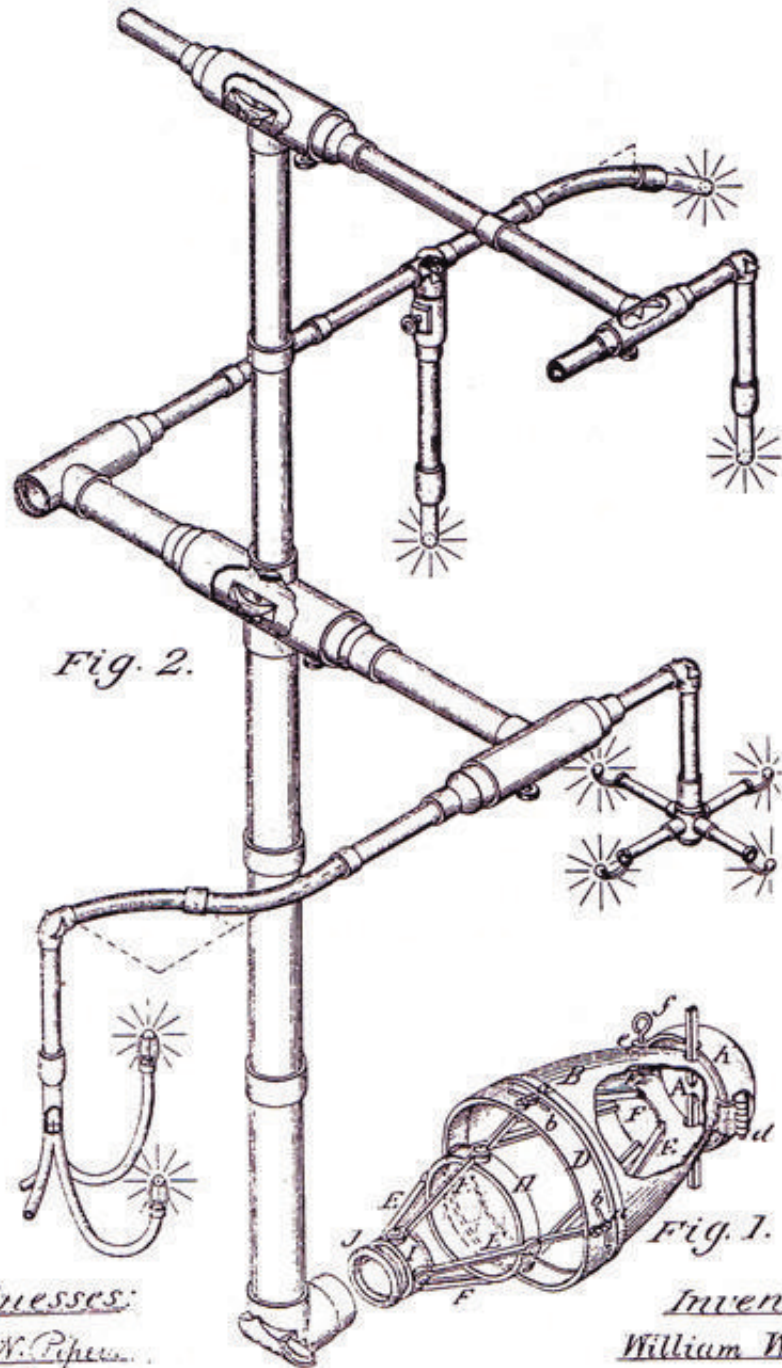


Fig. 2.

Fig. 1.

Witnesses:
J. N. Piper
Ed. [unclear]

Inventor:
William Wheeler
 by attorney
[unclear]

US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

Waveguiding

how does water surface look from bottom?



Waveguiding

from top partially transmitting!



Waveguiding

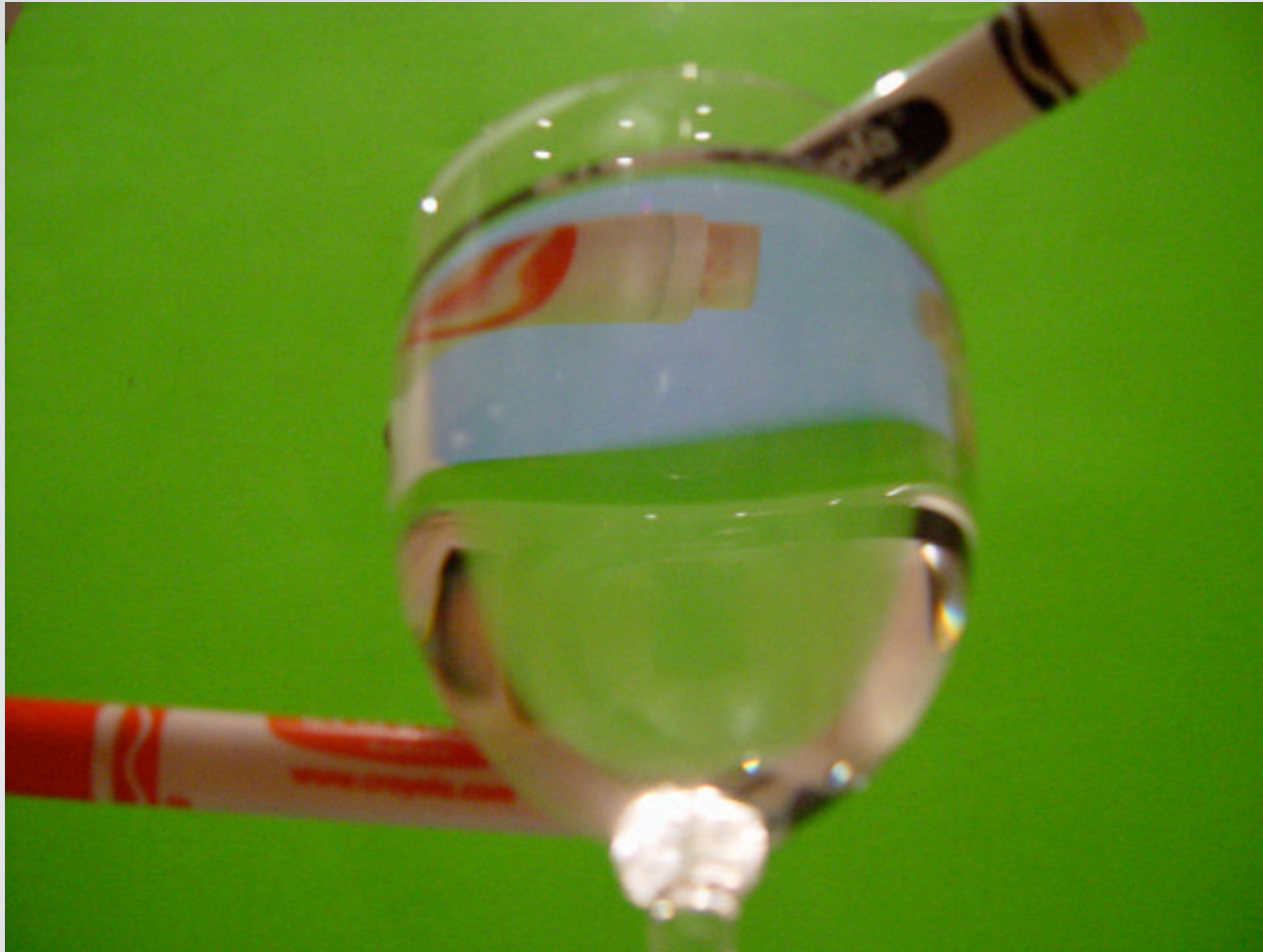


Waveguiding



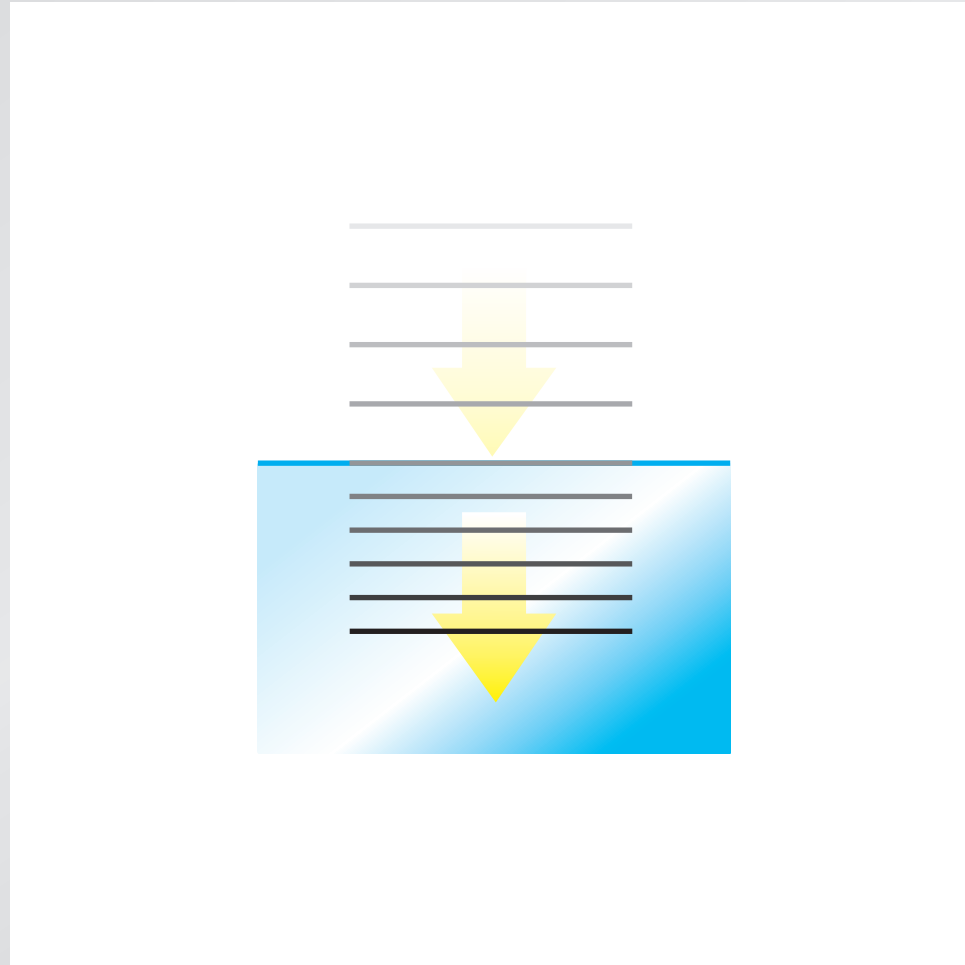
Waveguiding

water surface is perfect one-way mirror!



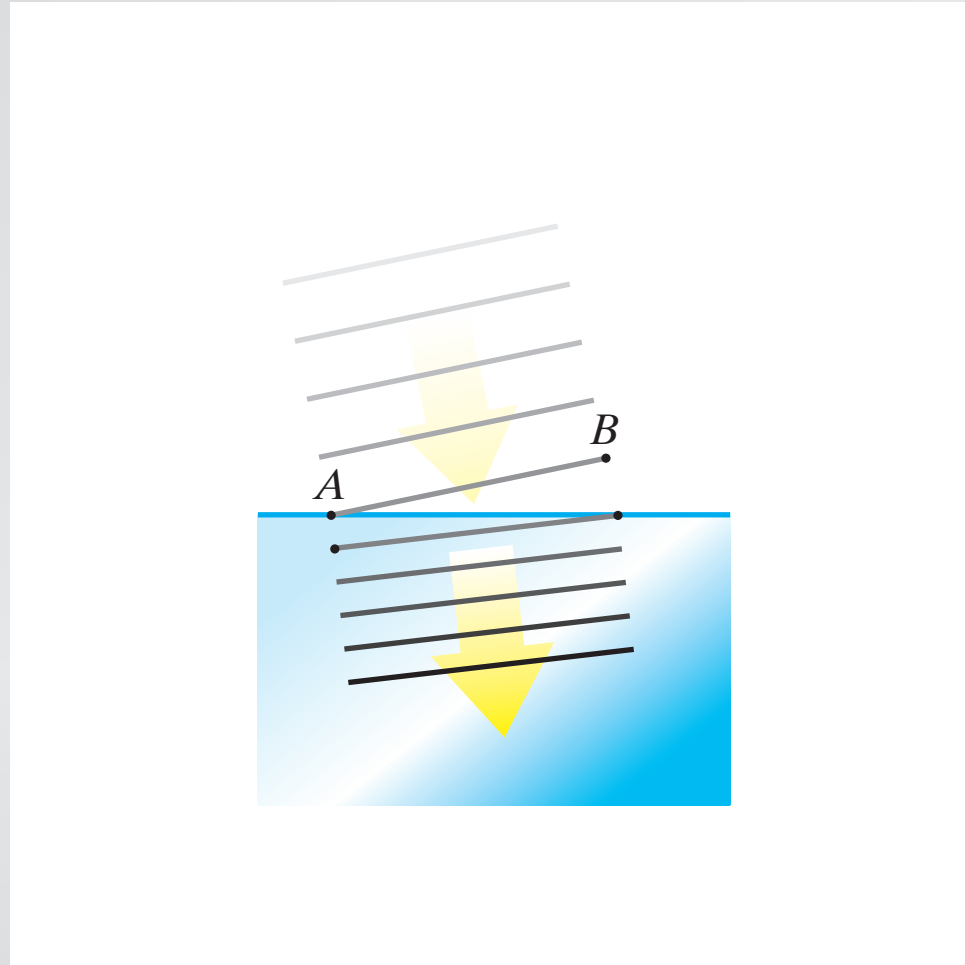
Waveguiding

Why? Because light travels more slowly in water...



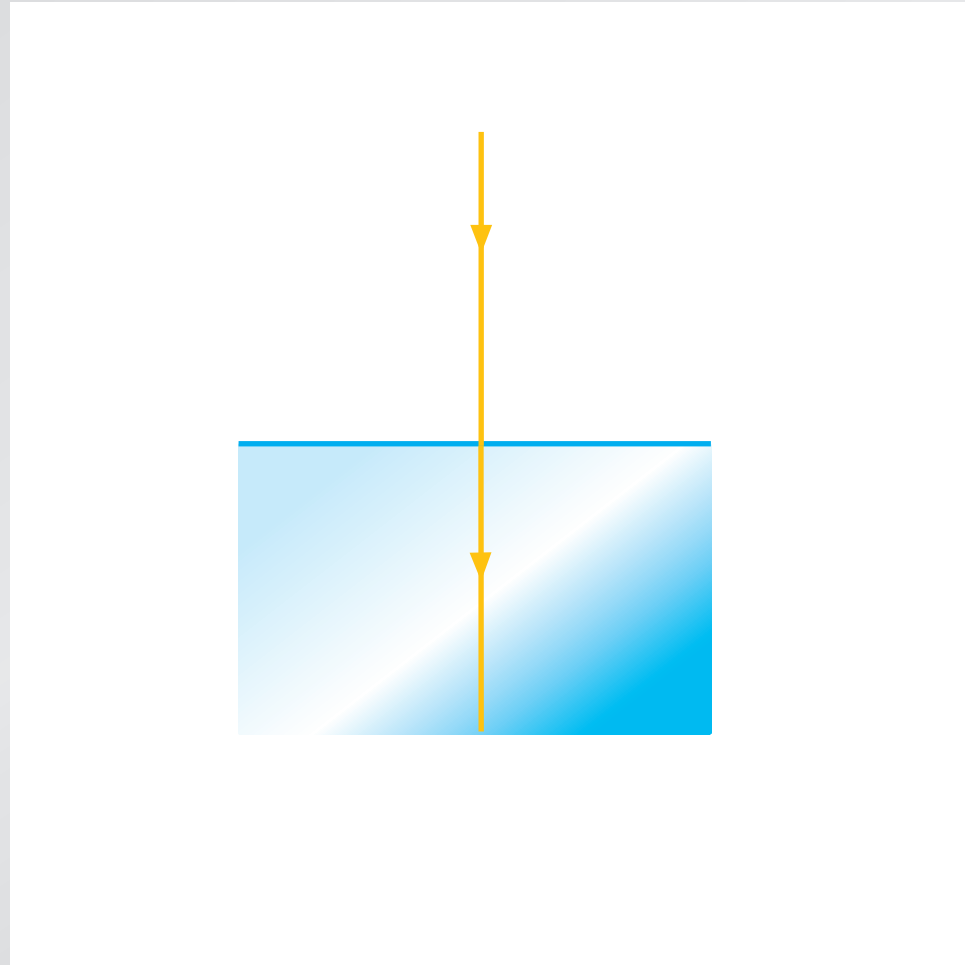
Waveguiding

...making it bend as it crosses surface



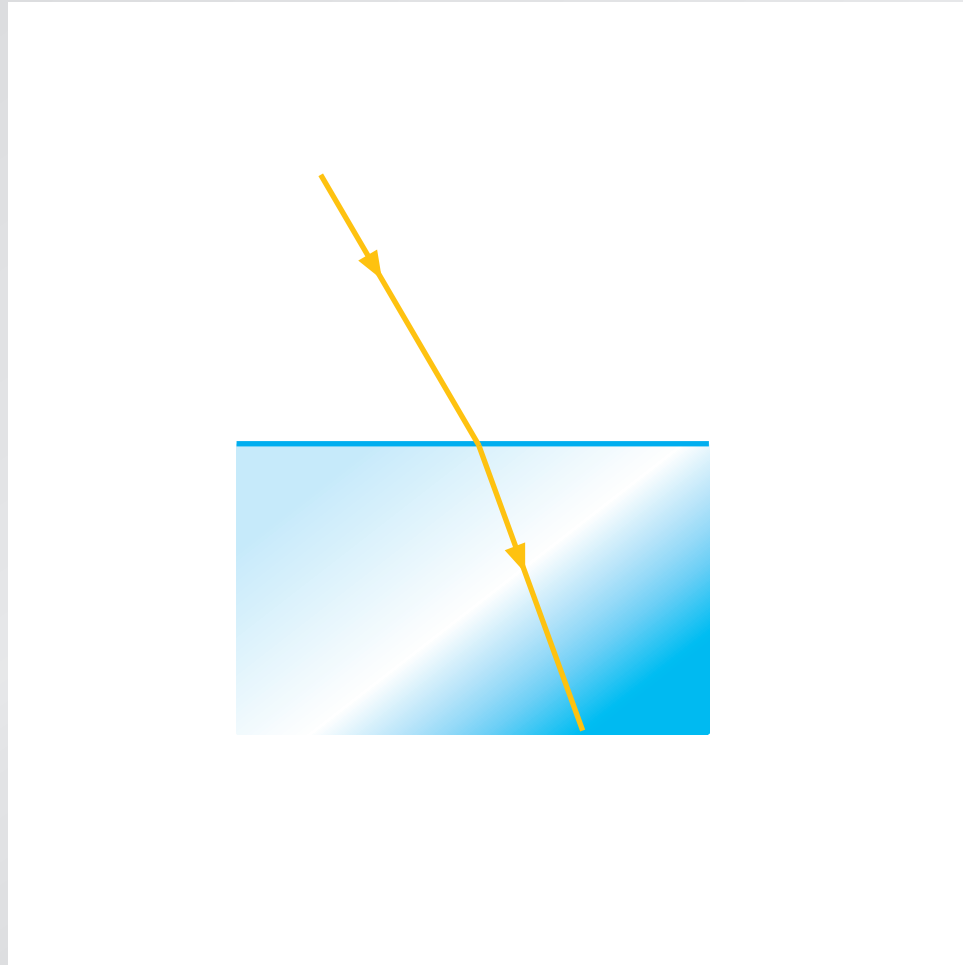
Waveguiding

The more angled the incident ray, the stronger the bending



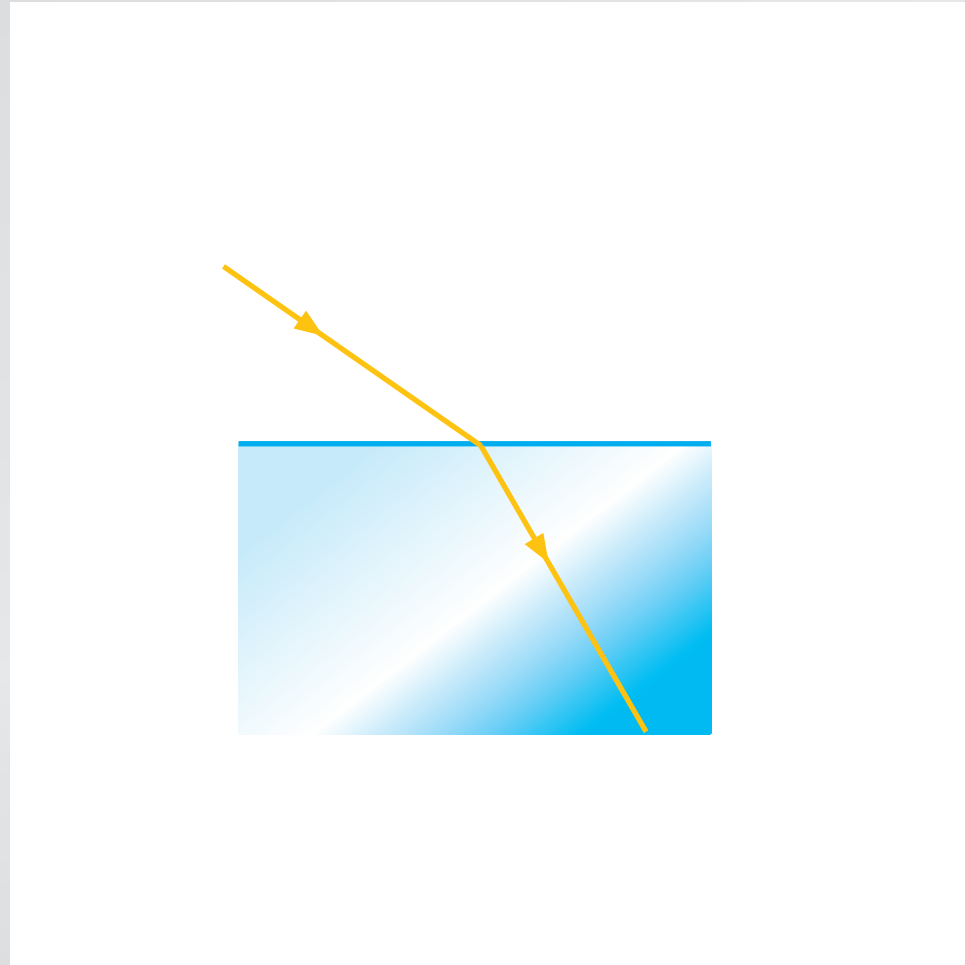
Waveguiding

The more angled the incident ray, the stronger the bending



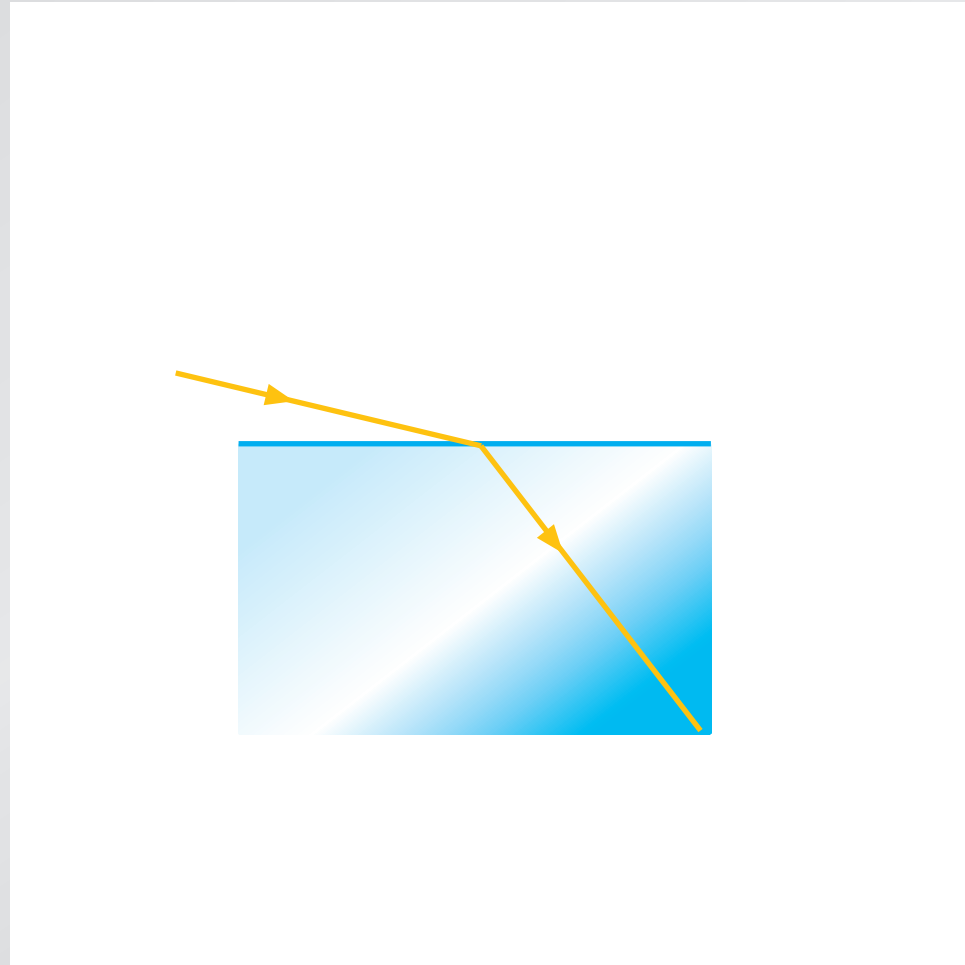
Waveguiding

The more angled the incident ray, the stronger the bending



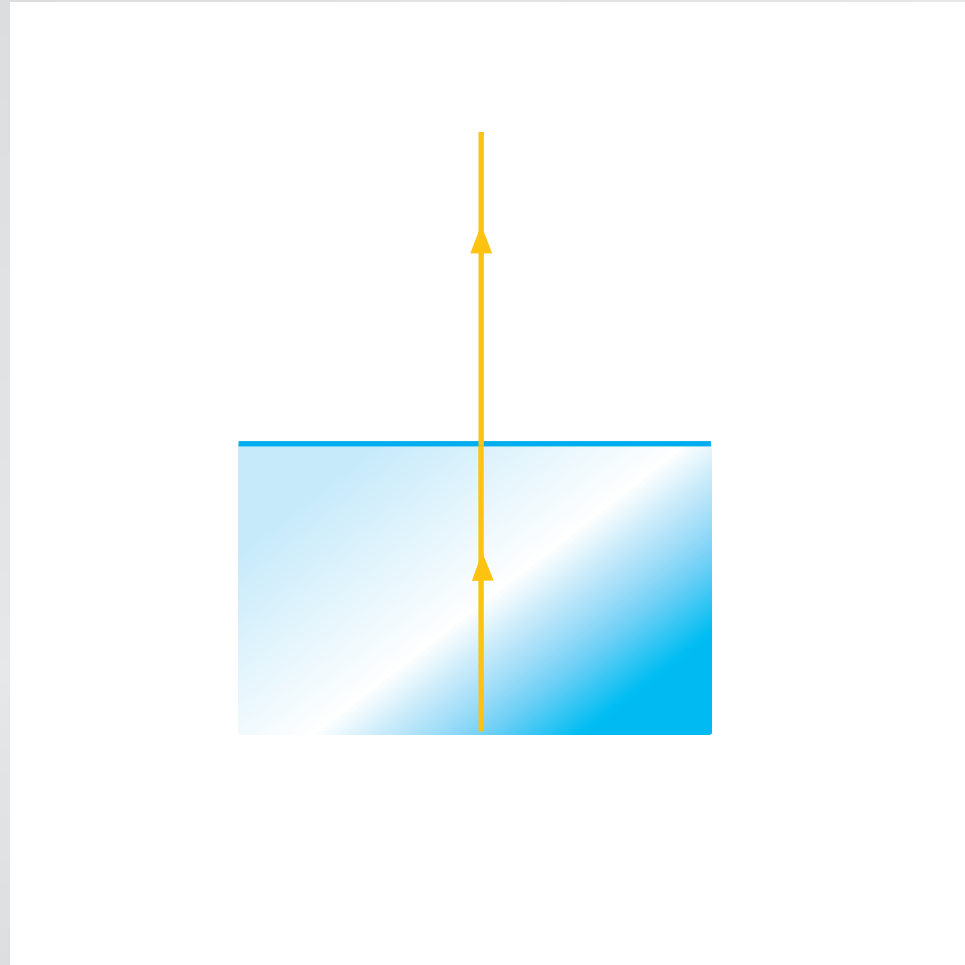
Waveguiding

The more angled the incident ray, the stronger the bending



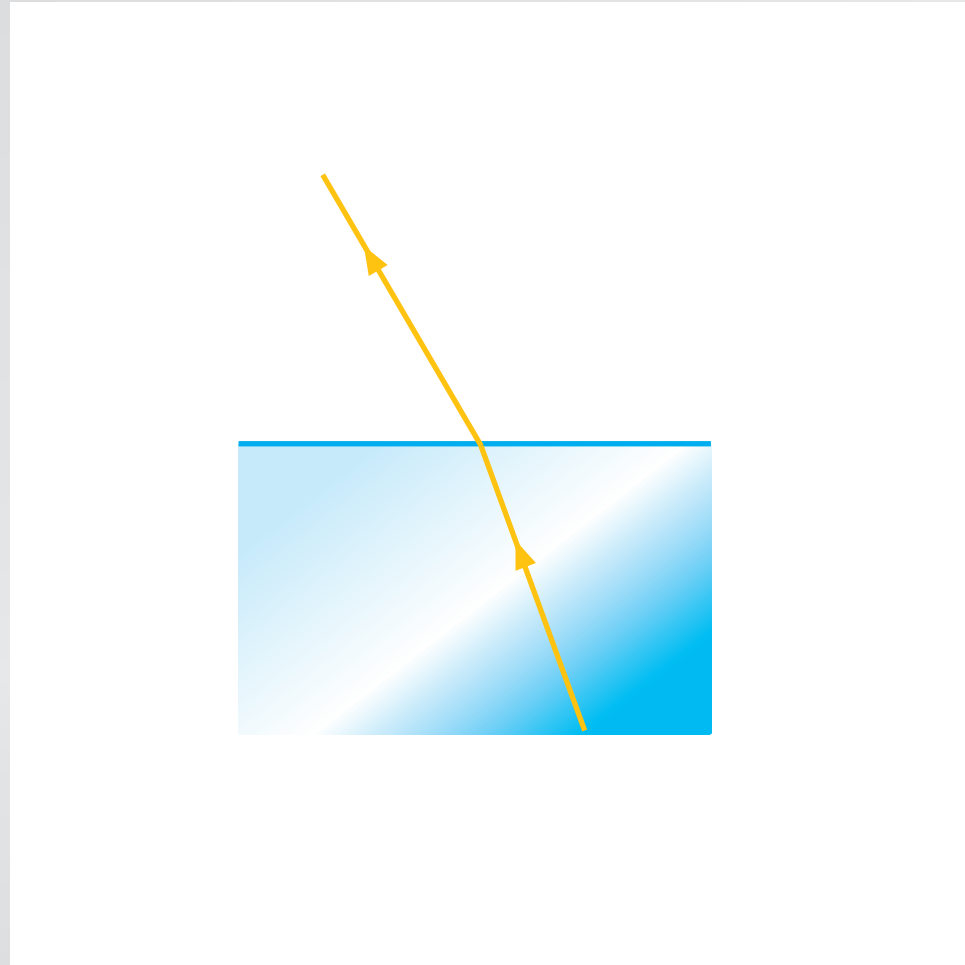
Waveguiding

The amount of bending is the same in reverse



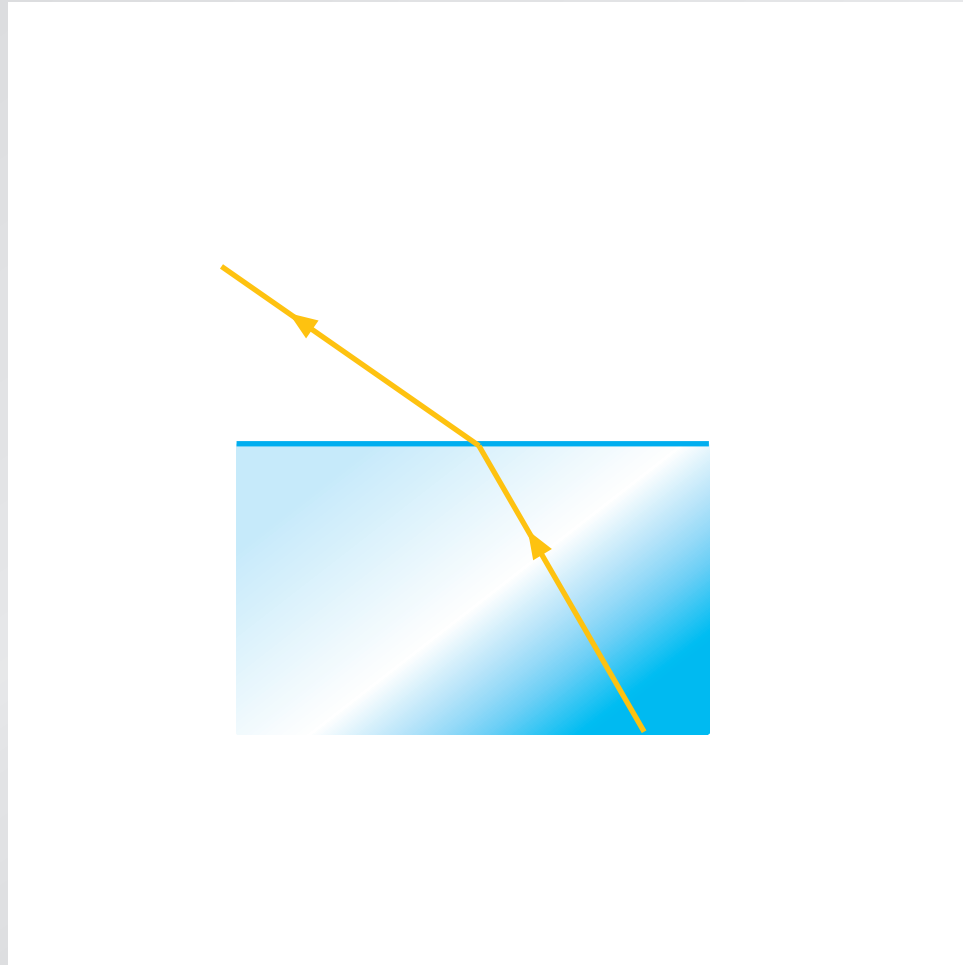
Waveguiding

The amount of bending is the same in reverse



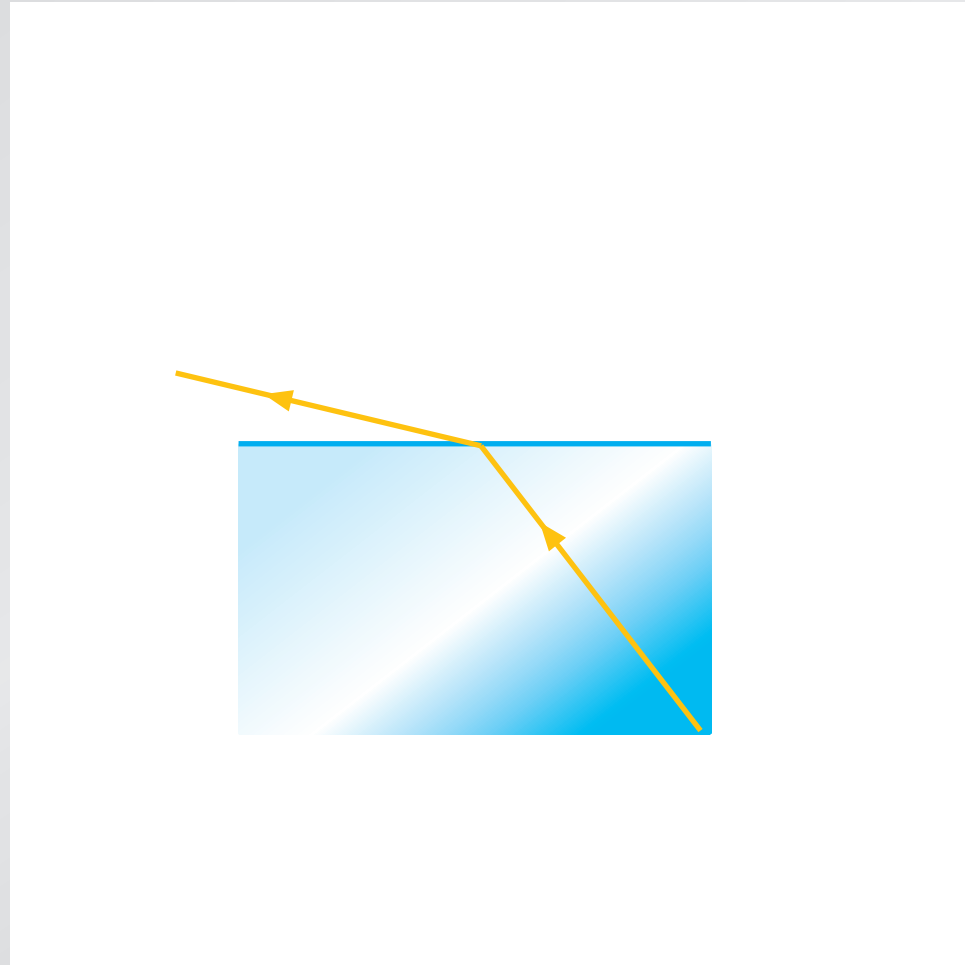
Waveguiding

The amount of bending is the same in reverse



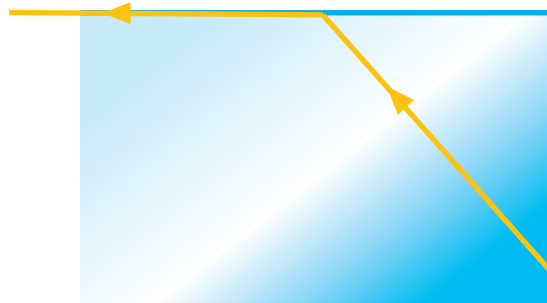
Waveguiding

The amount of bending is the same in reverse



Waveguiding

At 'critical angle' bent ray travels along surface



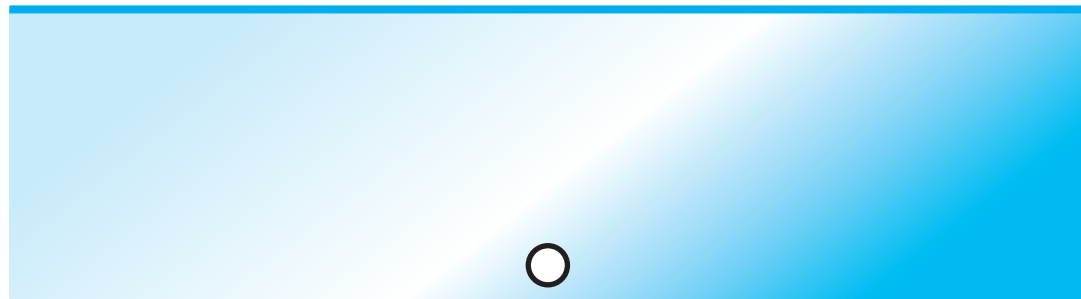
Waveguiding

Beyond 'critical angle': total internal reflection



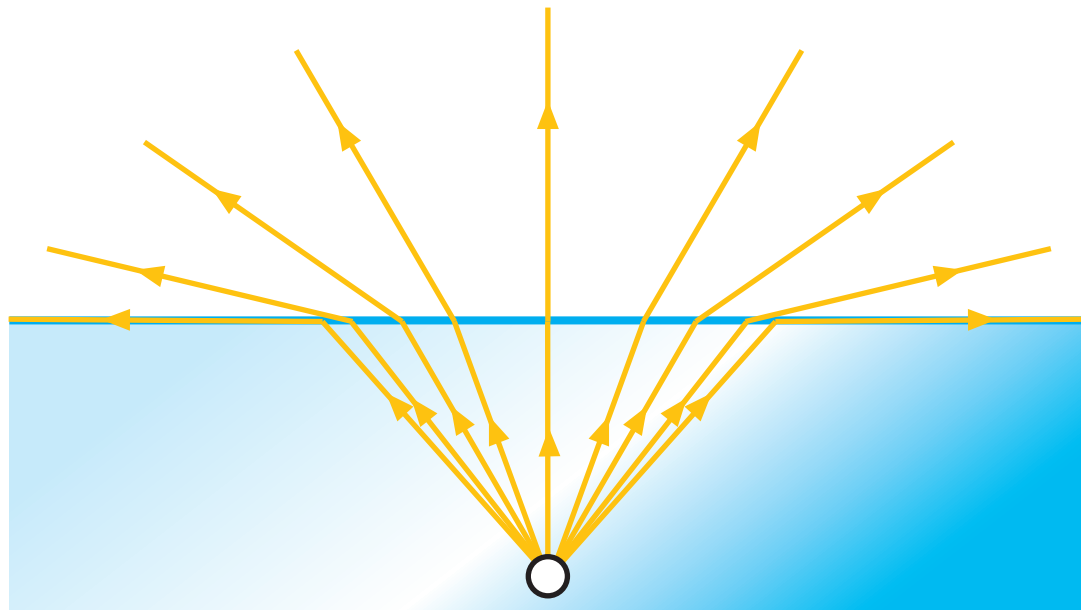
Waveguiding

seeing underwater



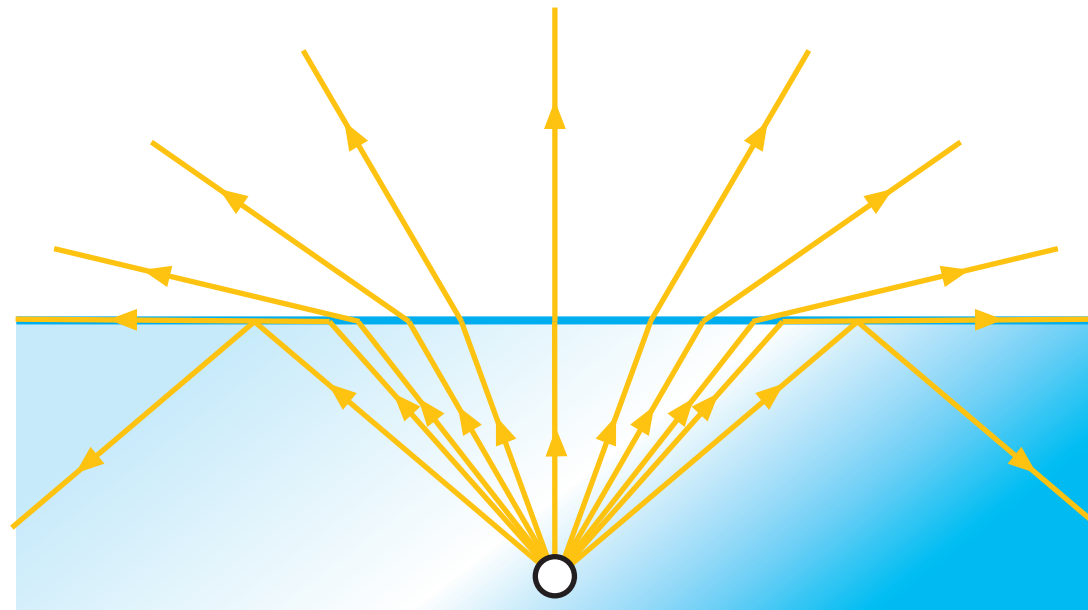
Waveguiding

seeing underwater



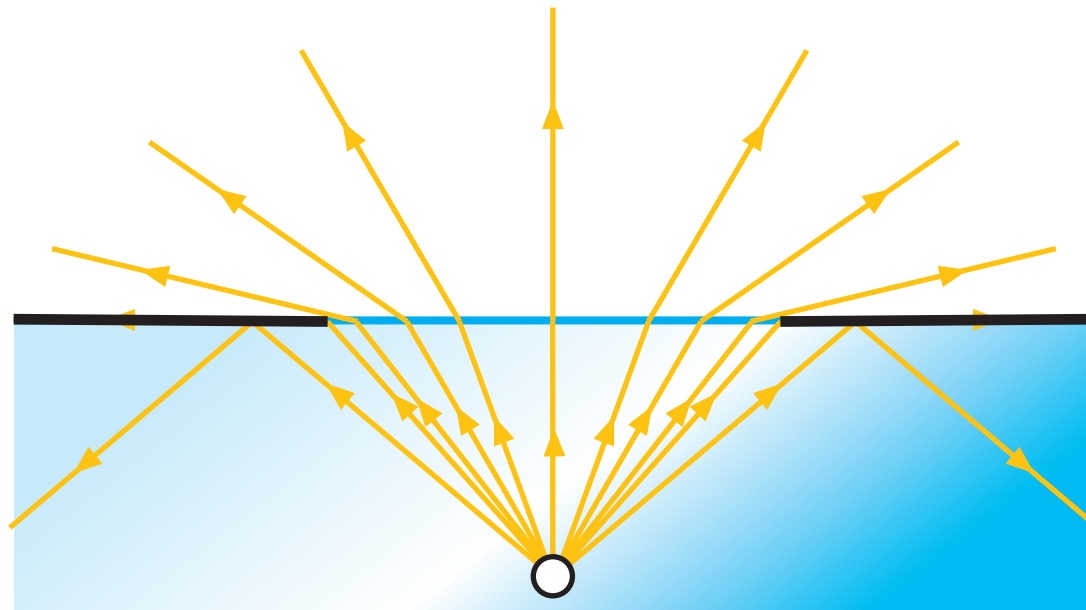
Waveguiding

seeing underwater



Waveguiding

surface looks like mirror with a circular hole



Waveguiding



Waveguiding



Waveguiding



Waveguiding

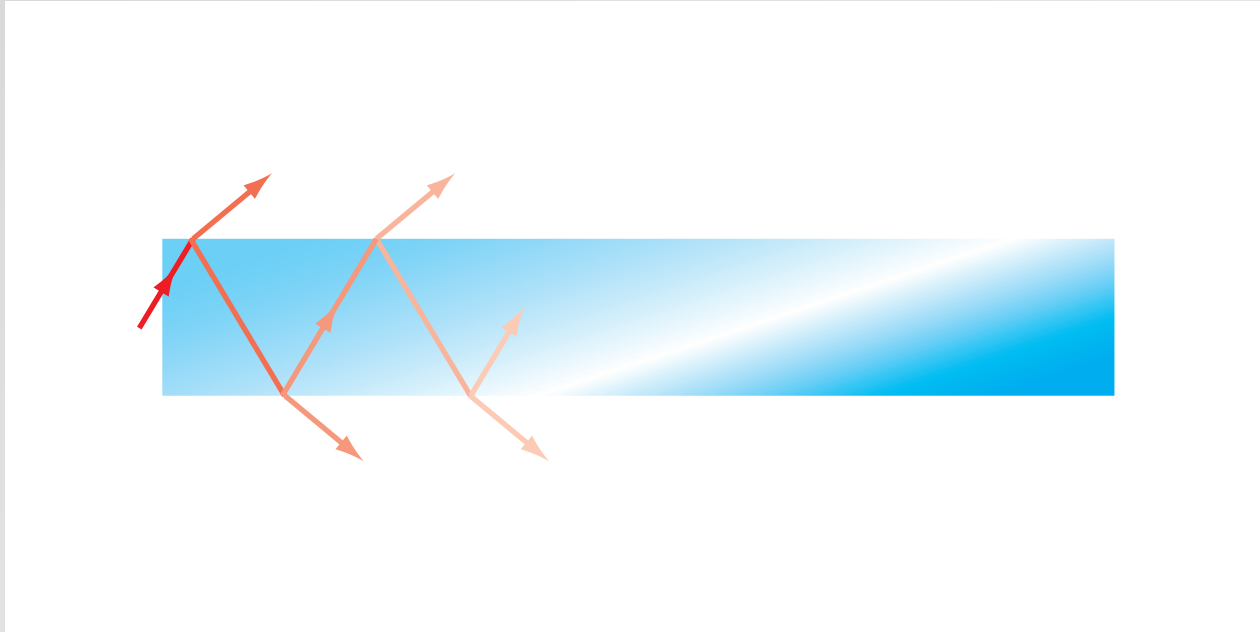


Waveguiding



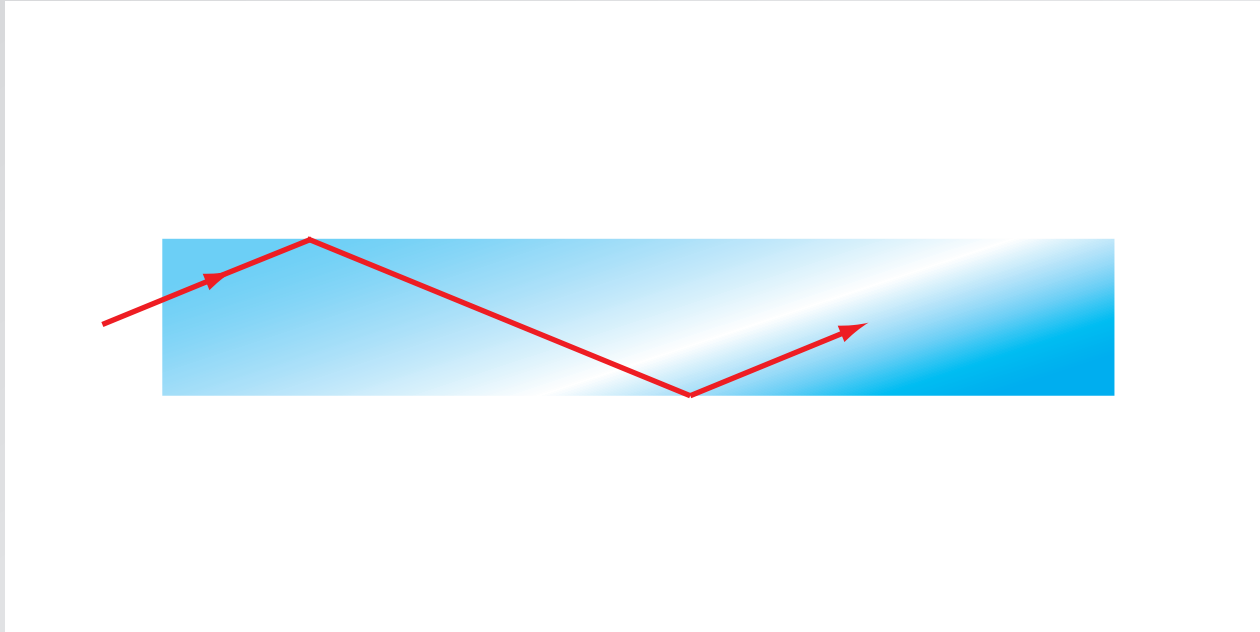
now consider a planar dielectric waveguide

Waveguiding



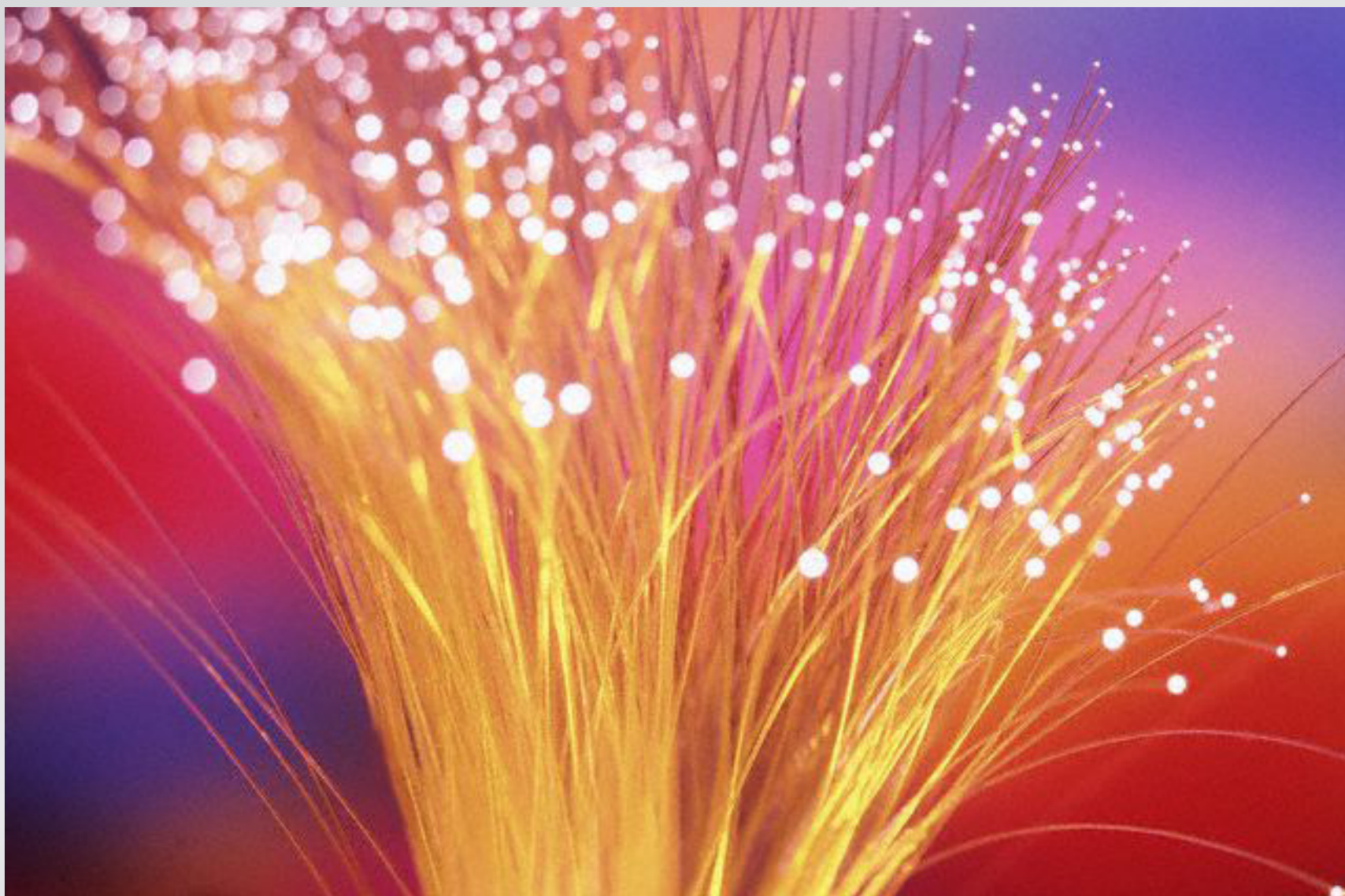
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

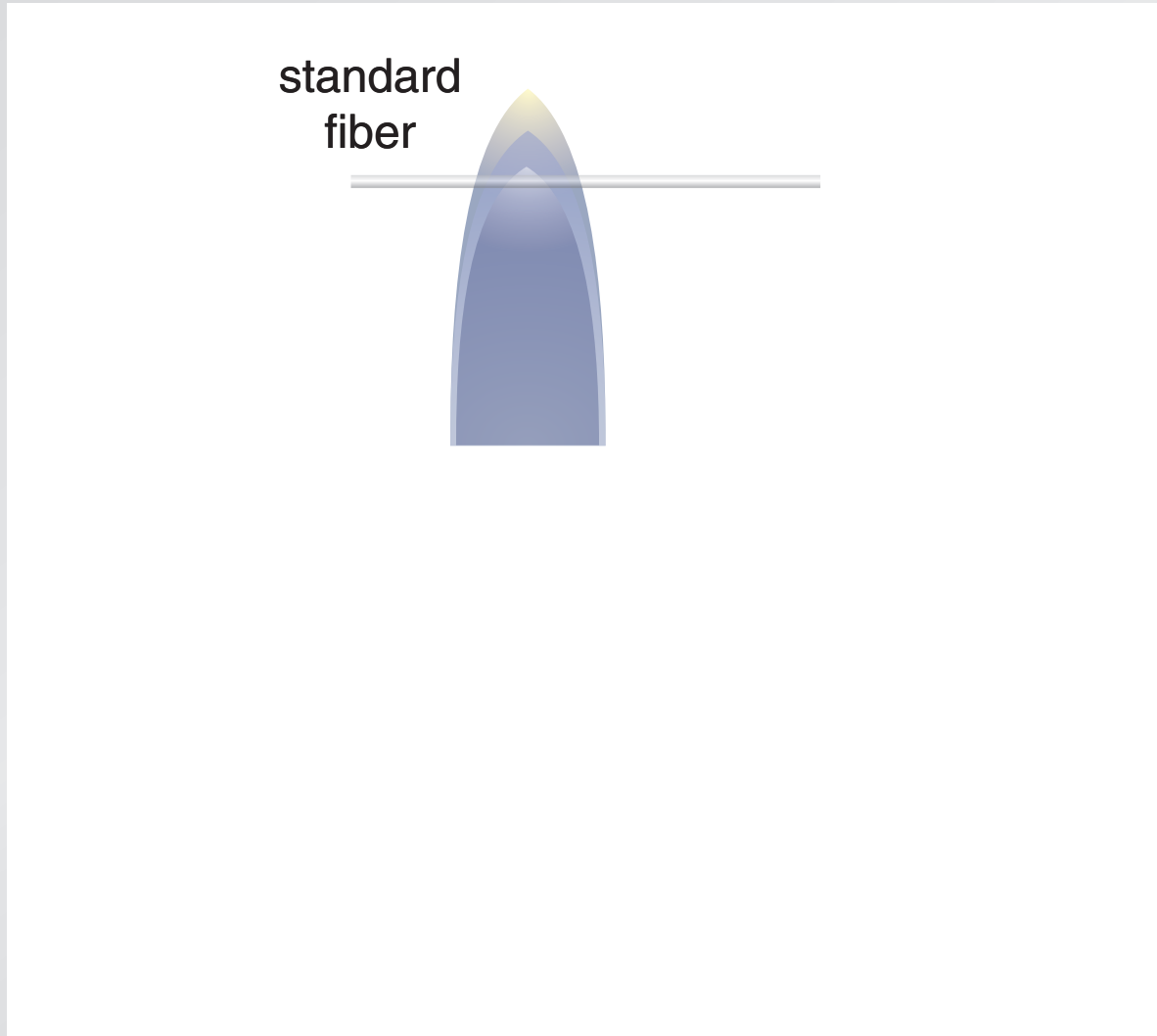
two-step drawing process

standard
fiber



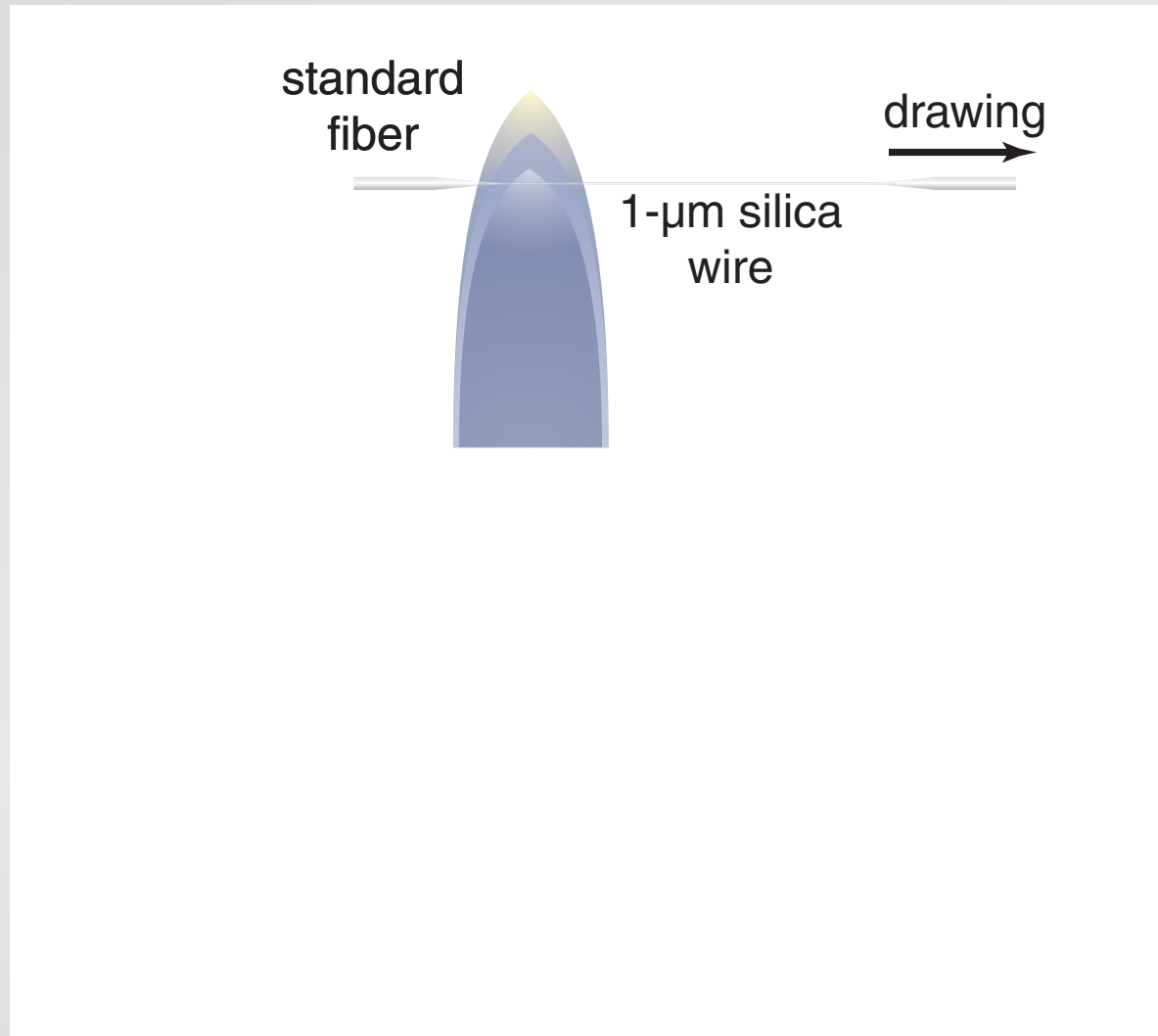
Nanowire fabrication

two-step drawing process



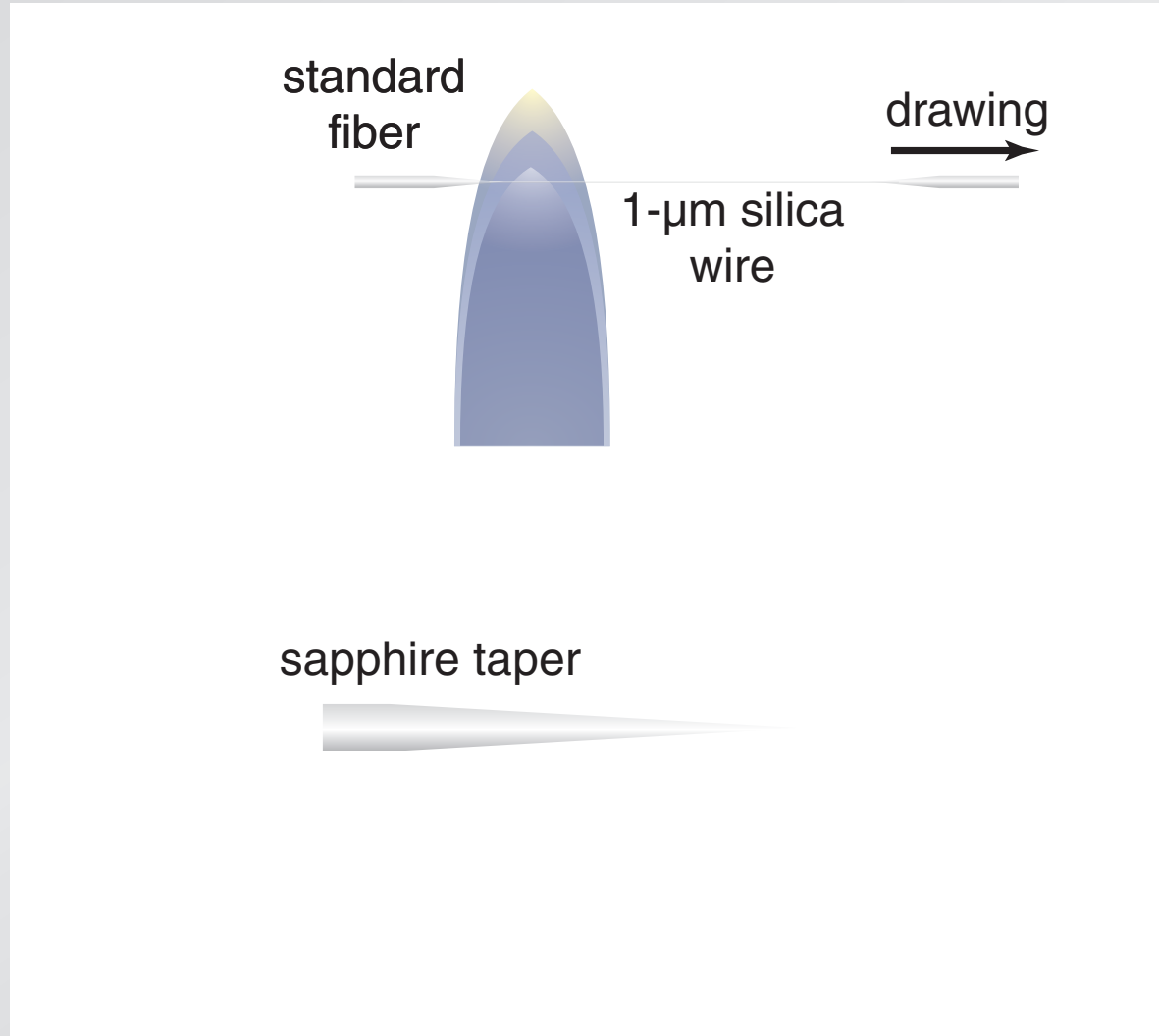
Nanowire fabrication

two-step drawing process



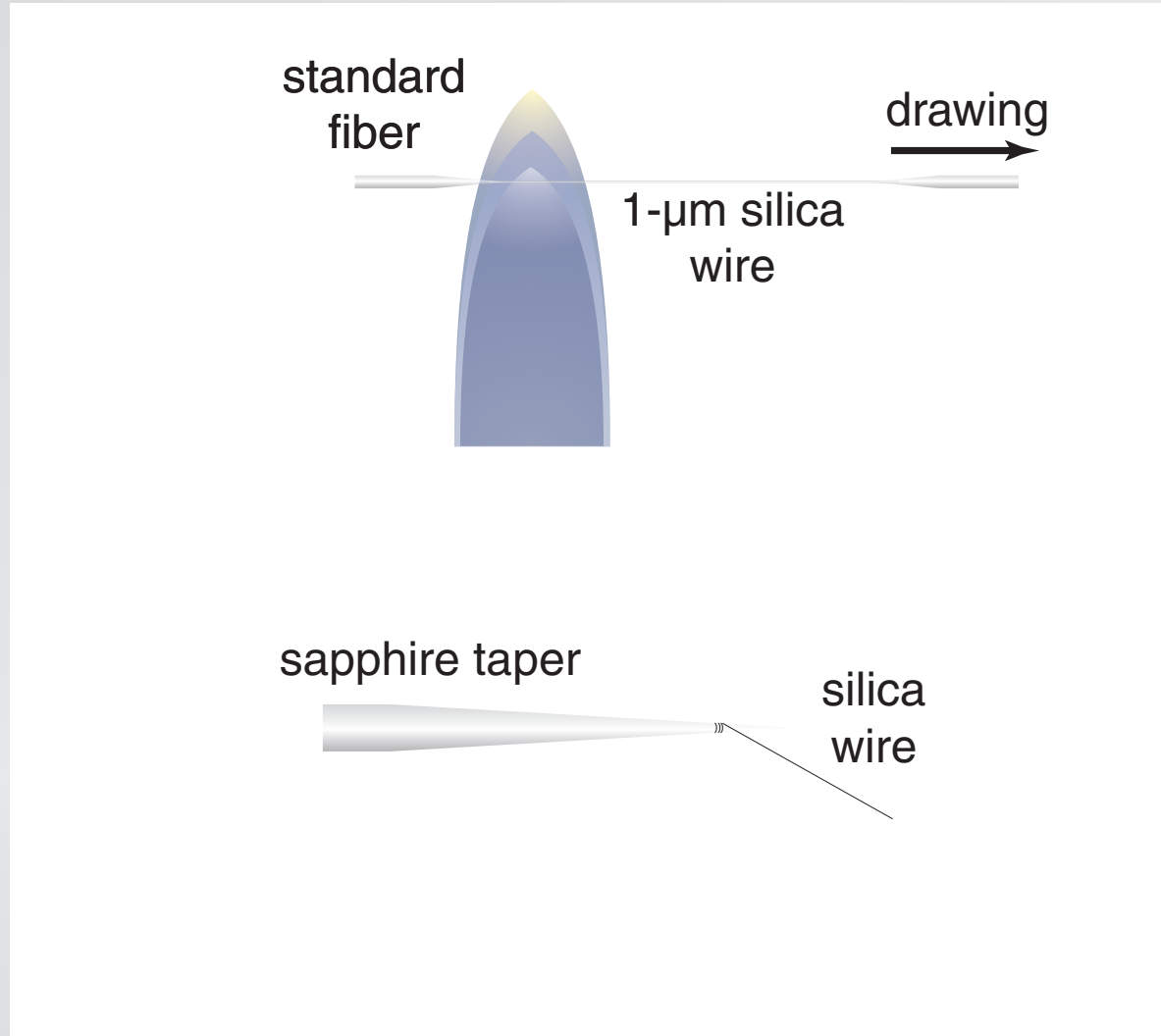
Nanowire fabrication

two-step drawing process



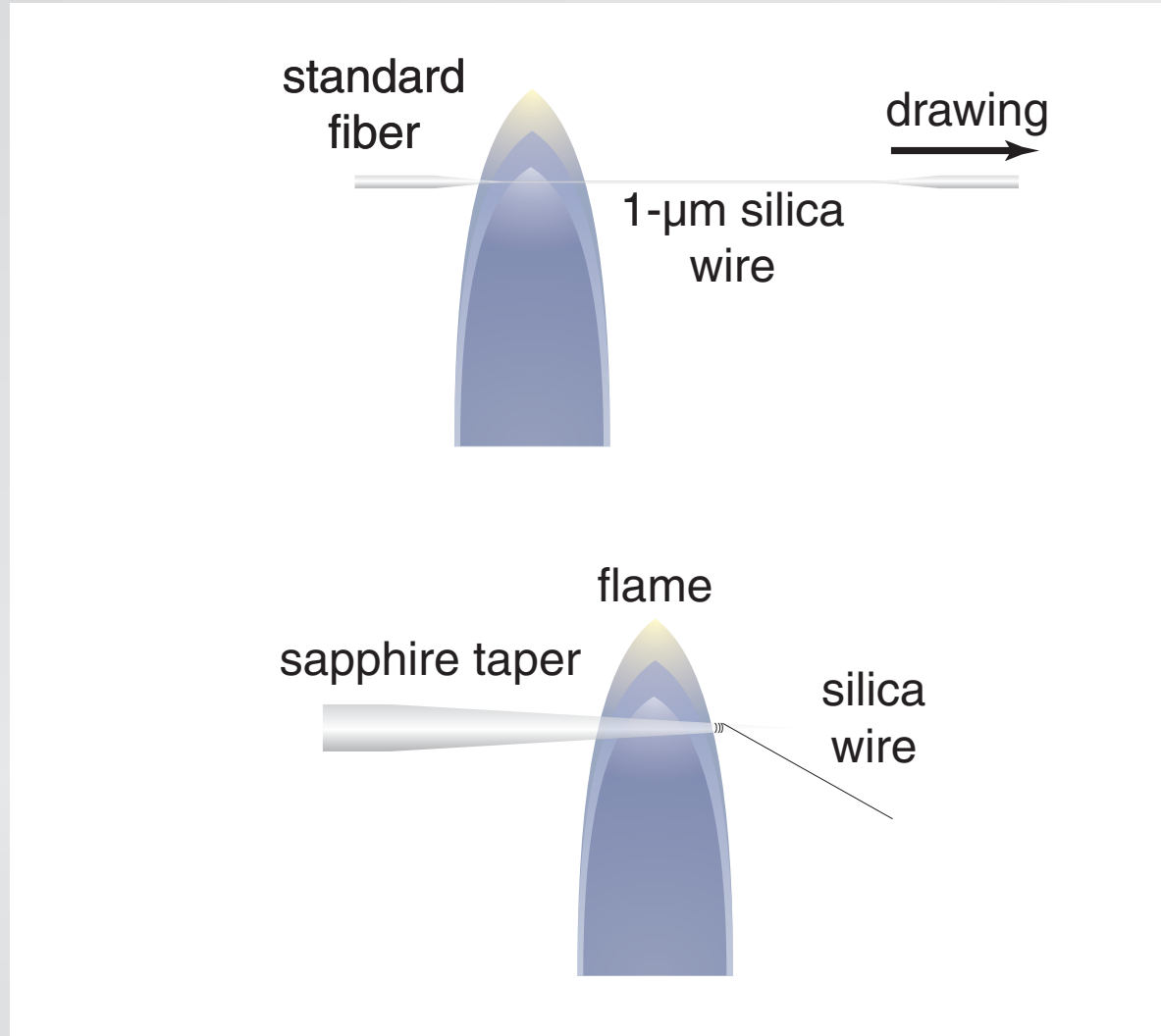
Nanowire fabrication

two-step drawing process



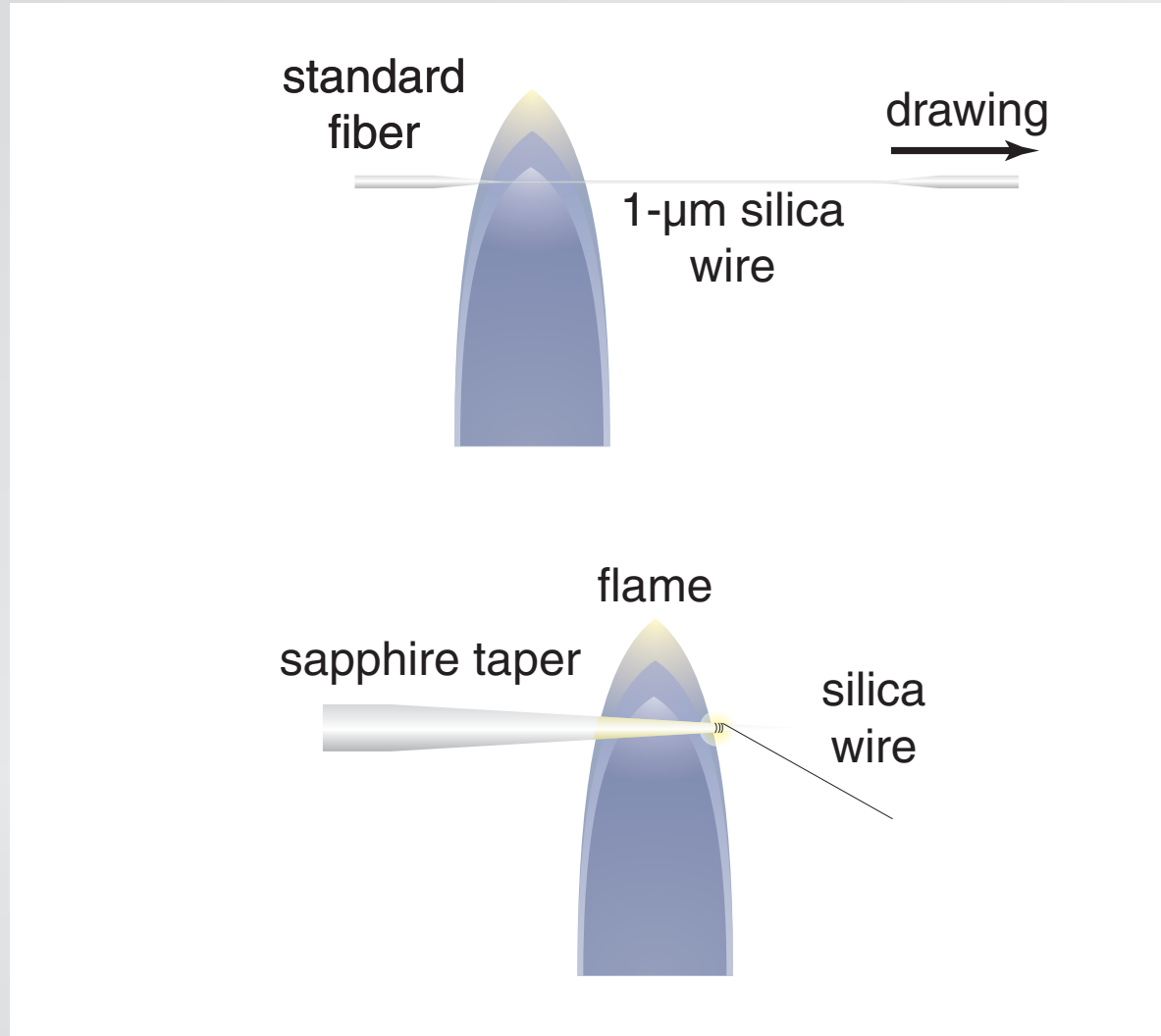
Nanowire fabrication

two-step drawing process



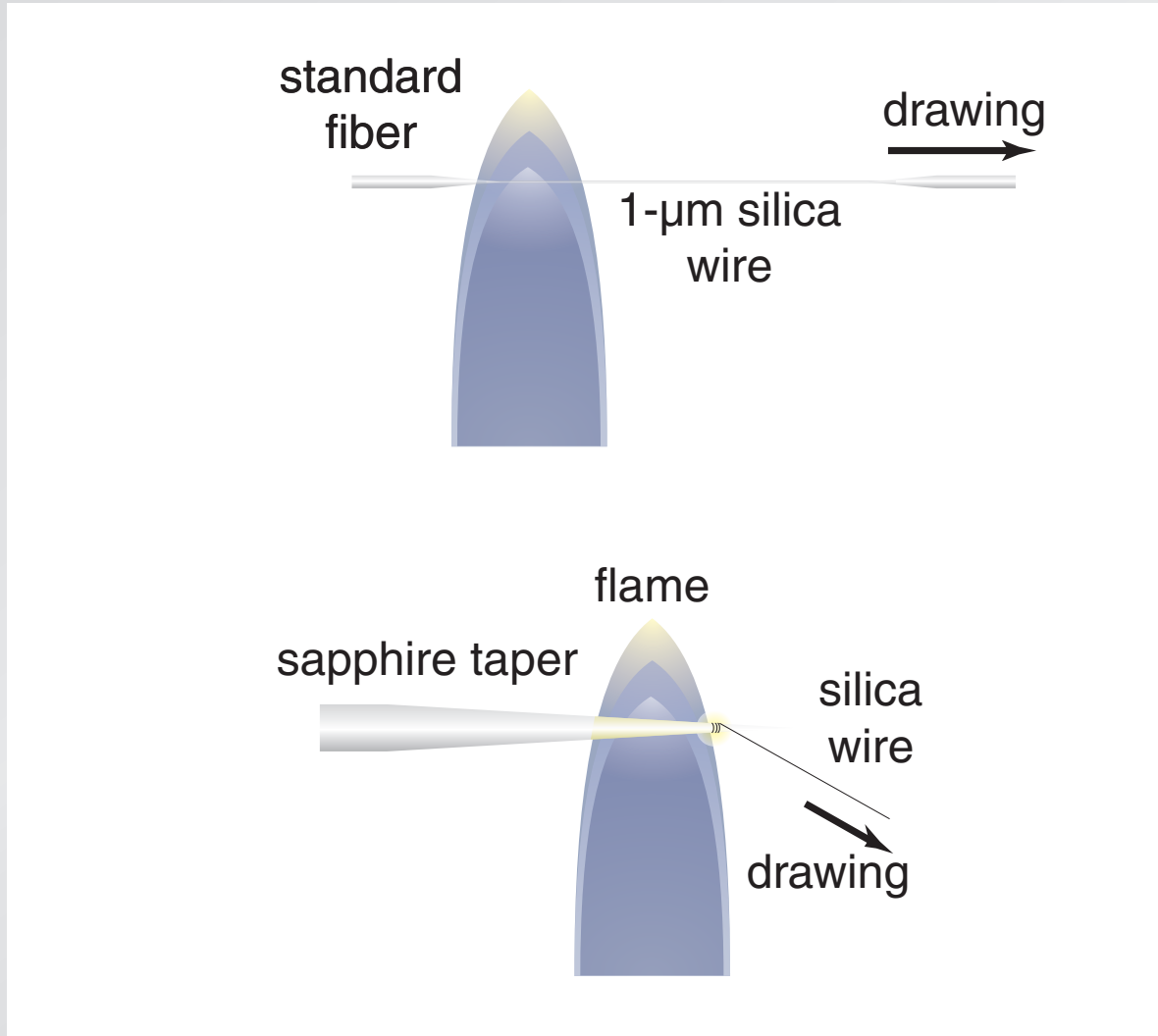
Nanowire fabrication

two-step drawing process

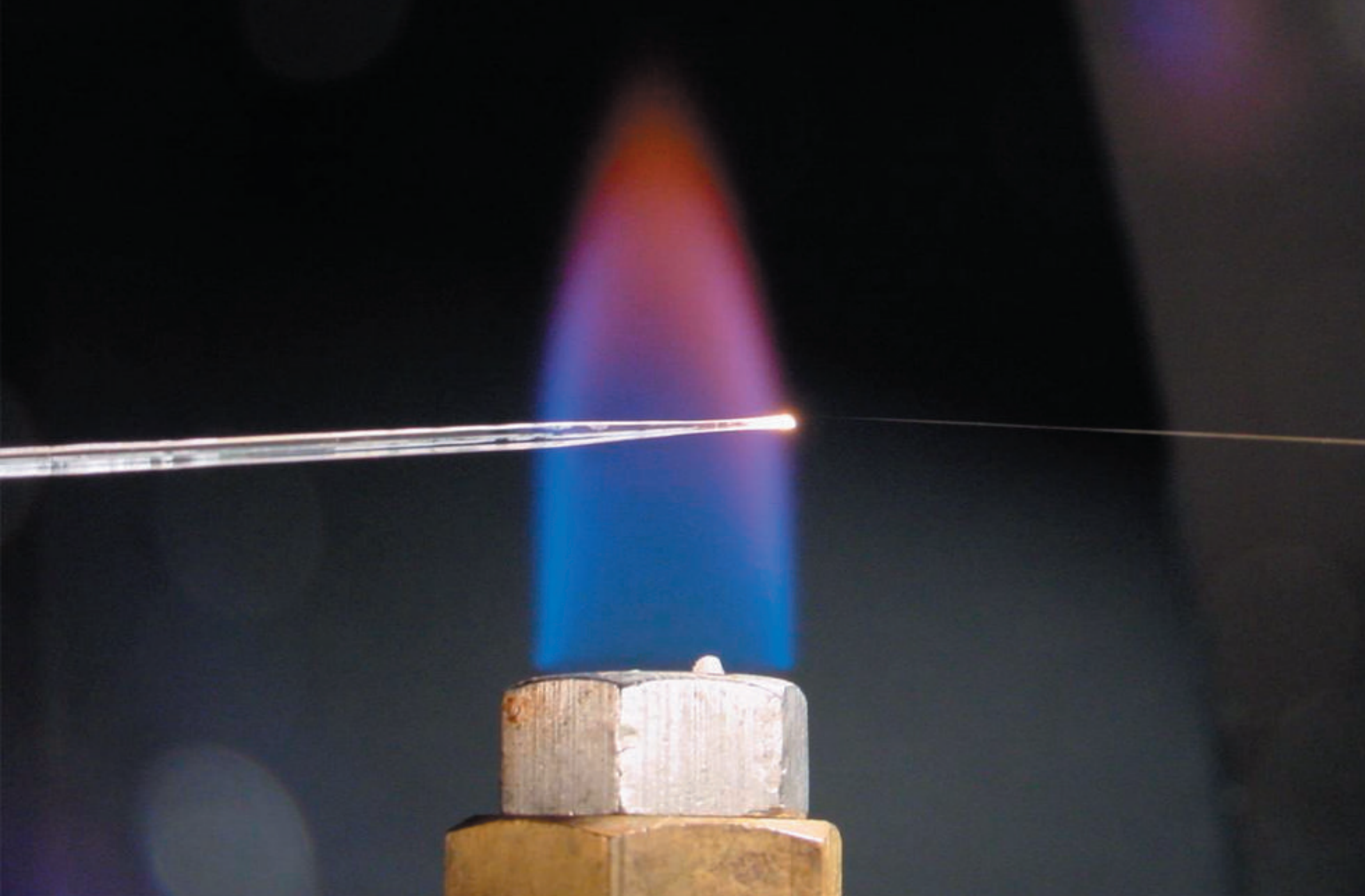


Nanowire fabrication

two-step drawing process



Nanowire fabrication



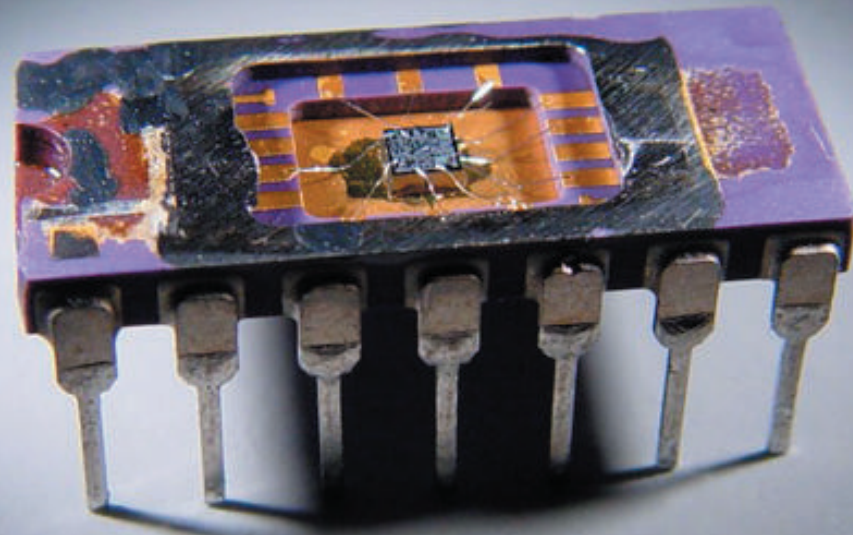
Nanowire fabrication

1 μm

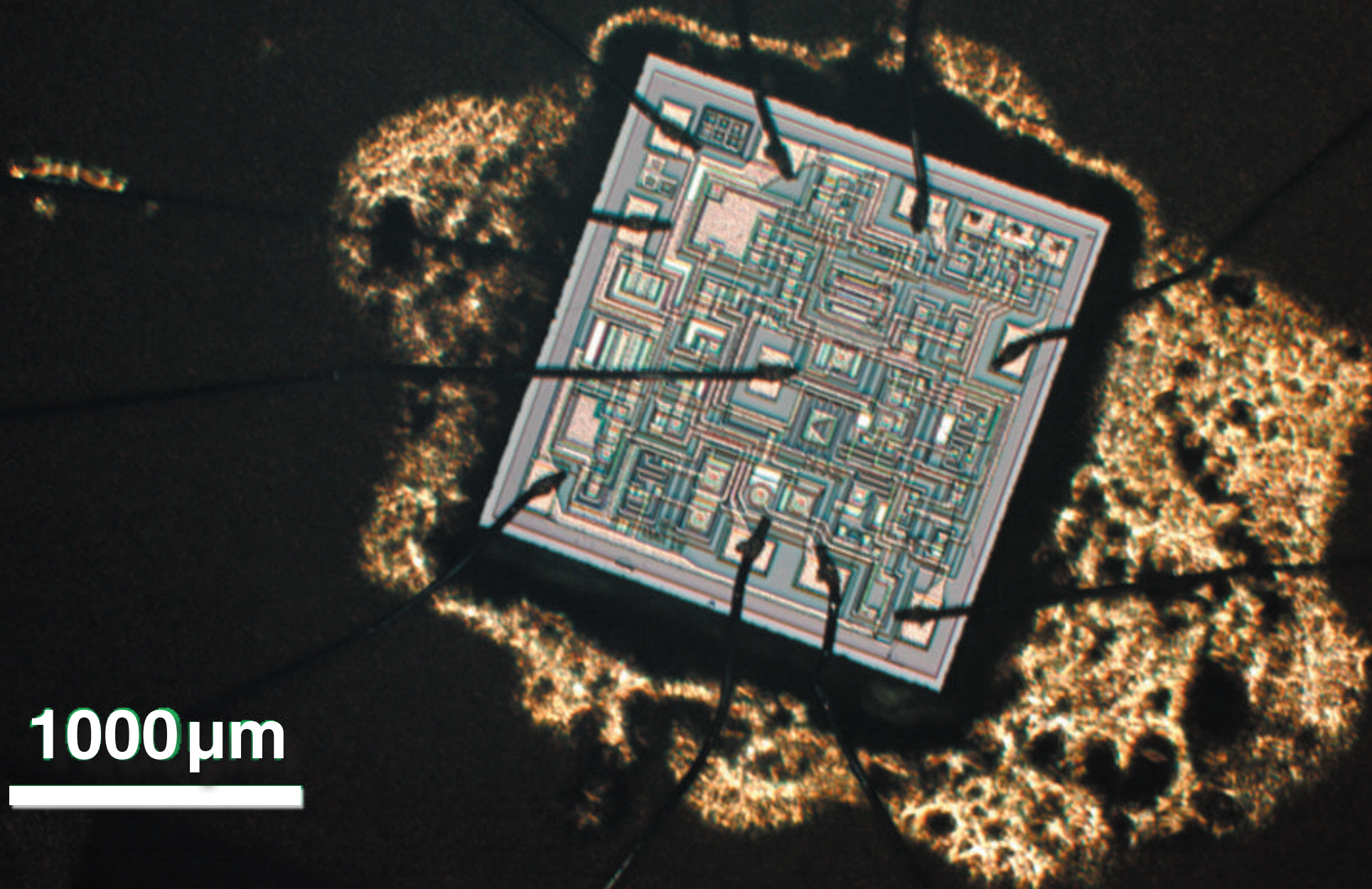


Nature, 426, 816 (2003)

Nanowire fabrication

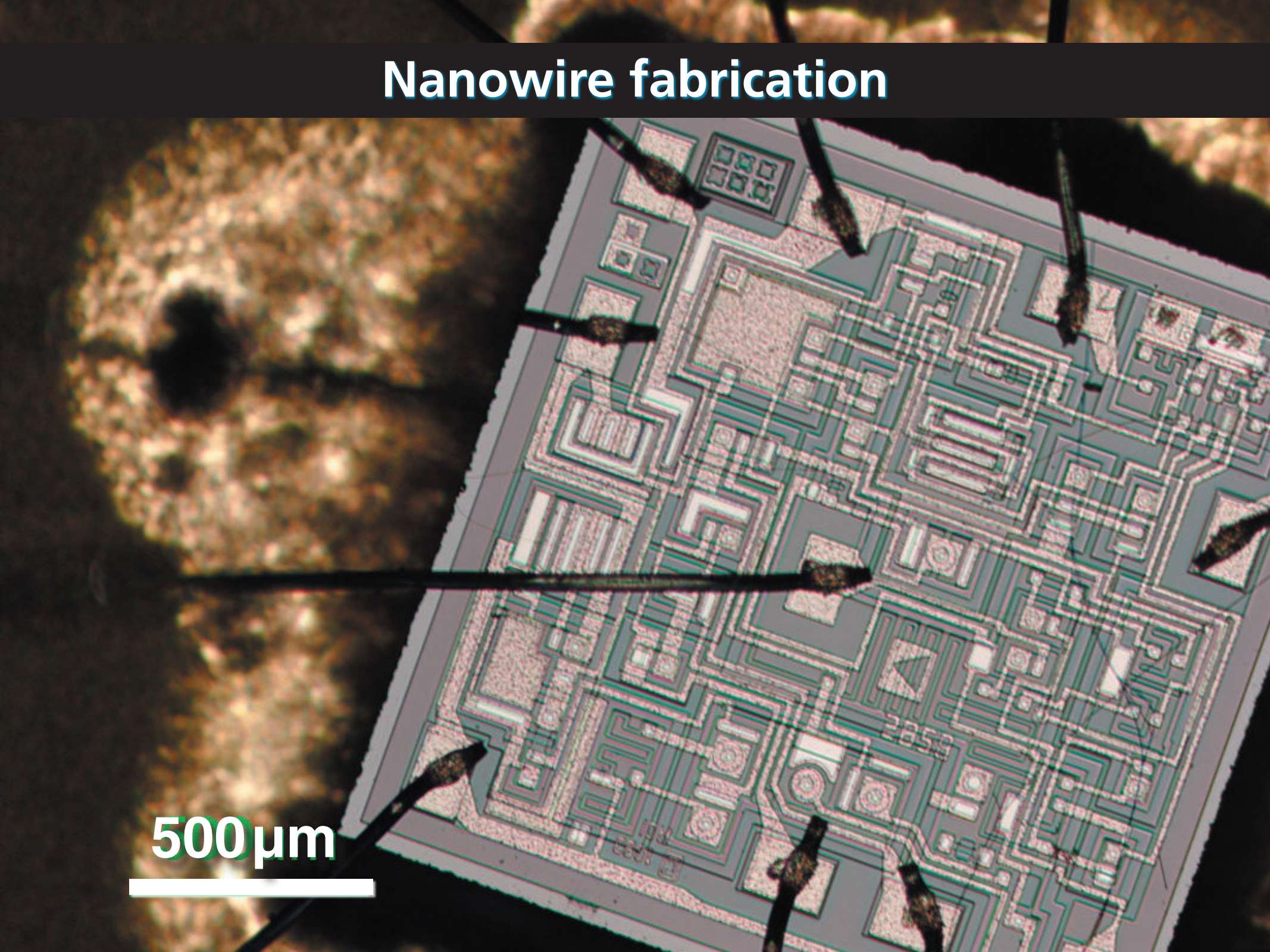


Nanowire fabrication

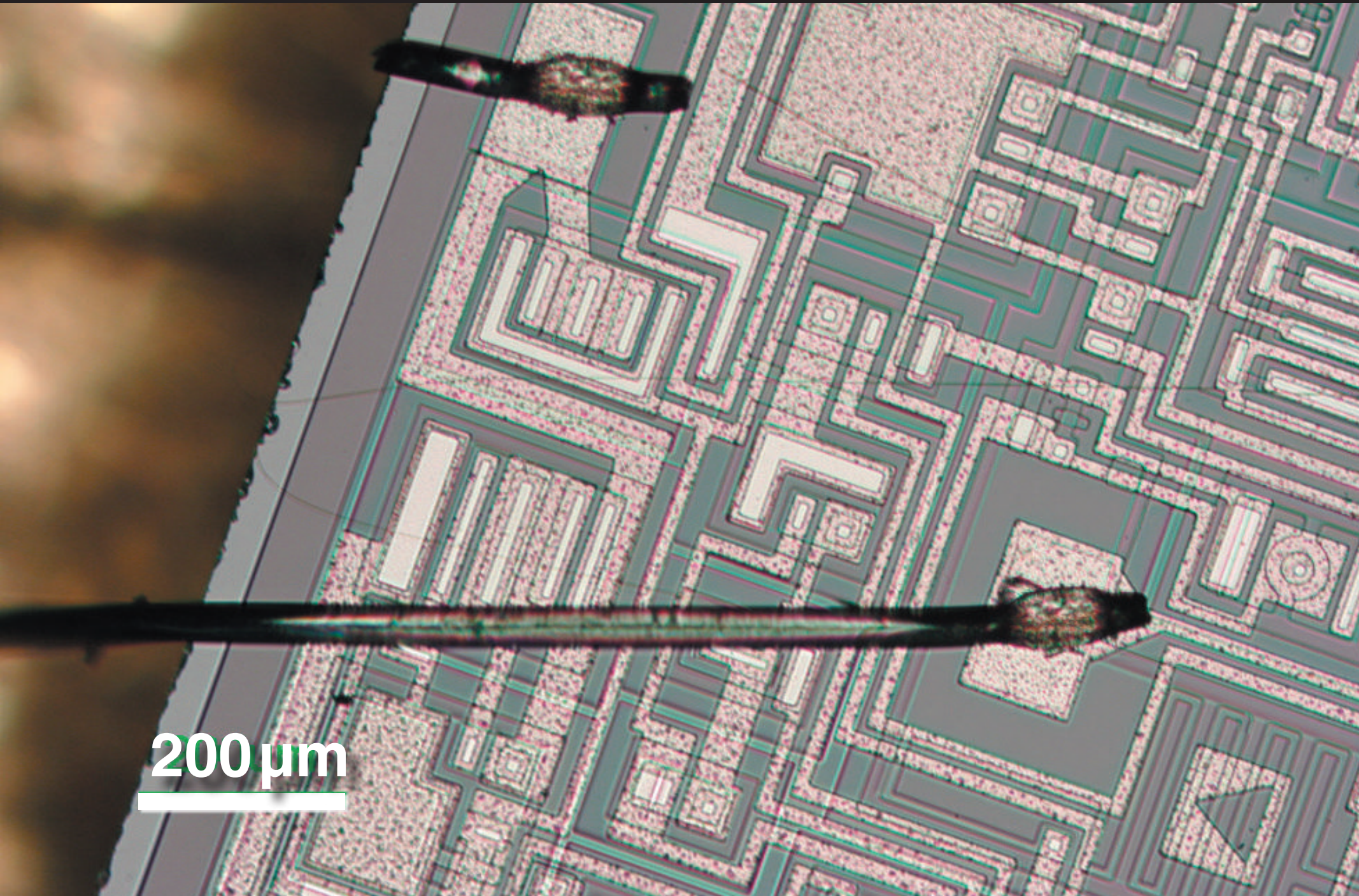


Nanowire fabrication

500 μm

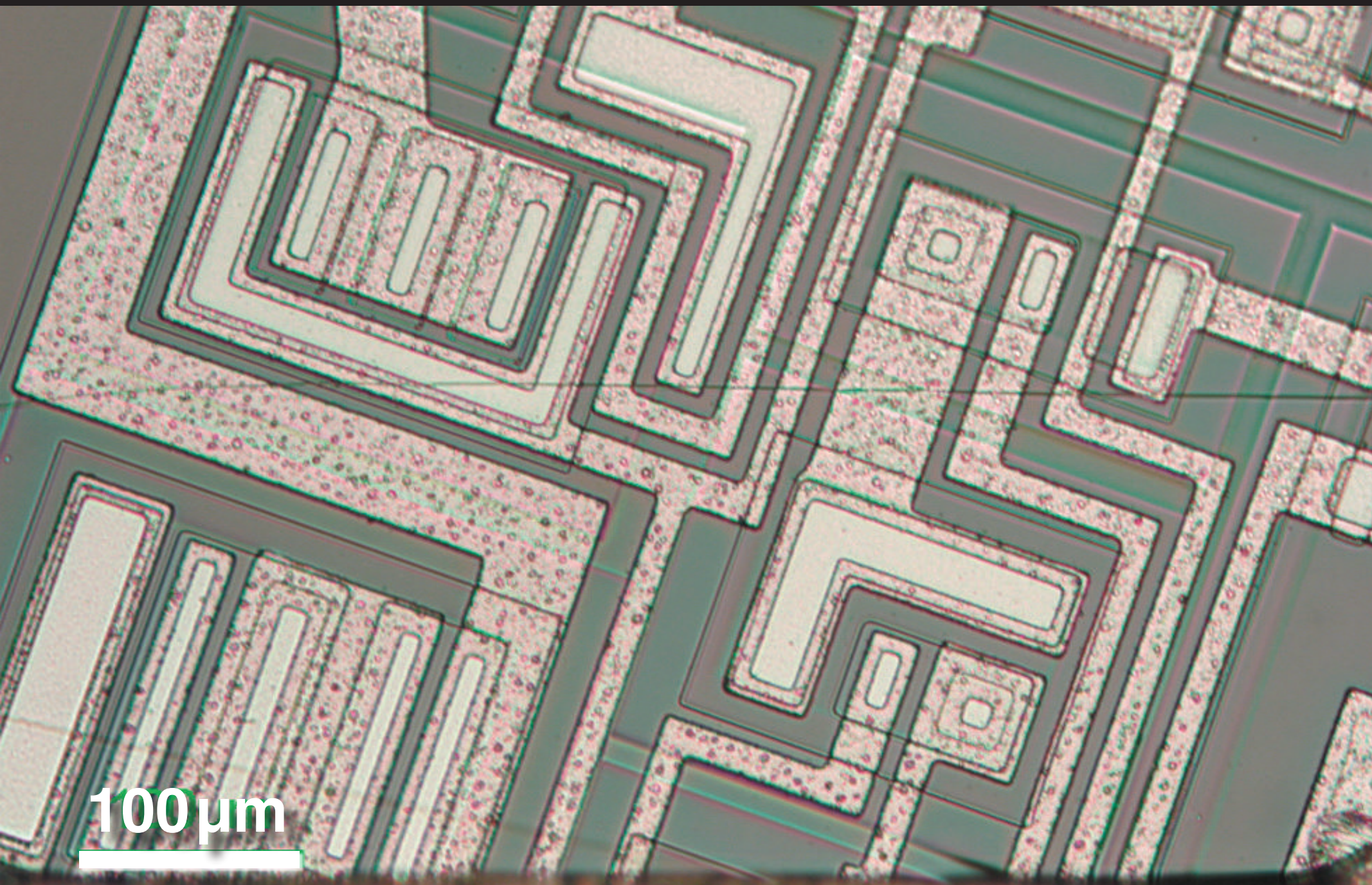


Nanowire fabrication

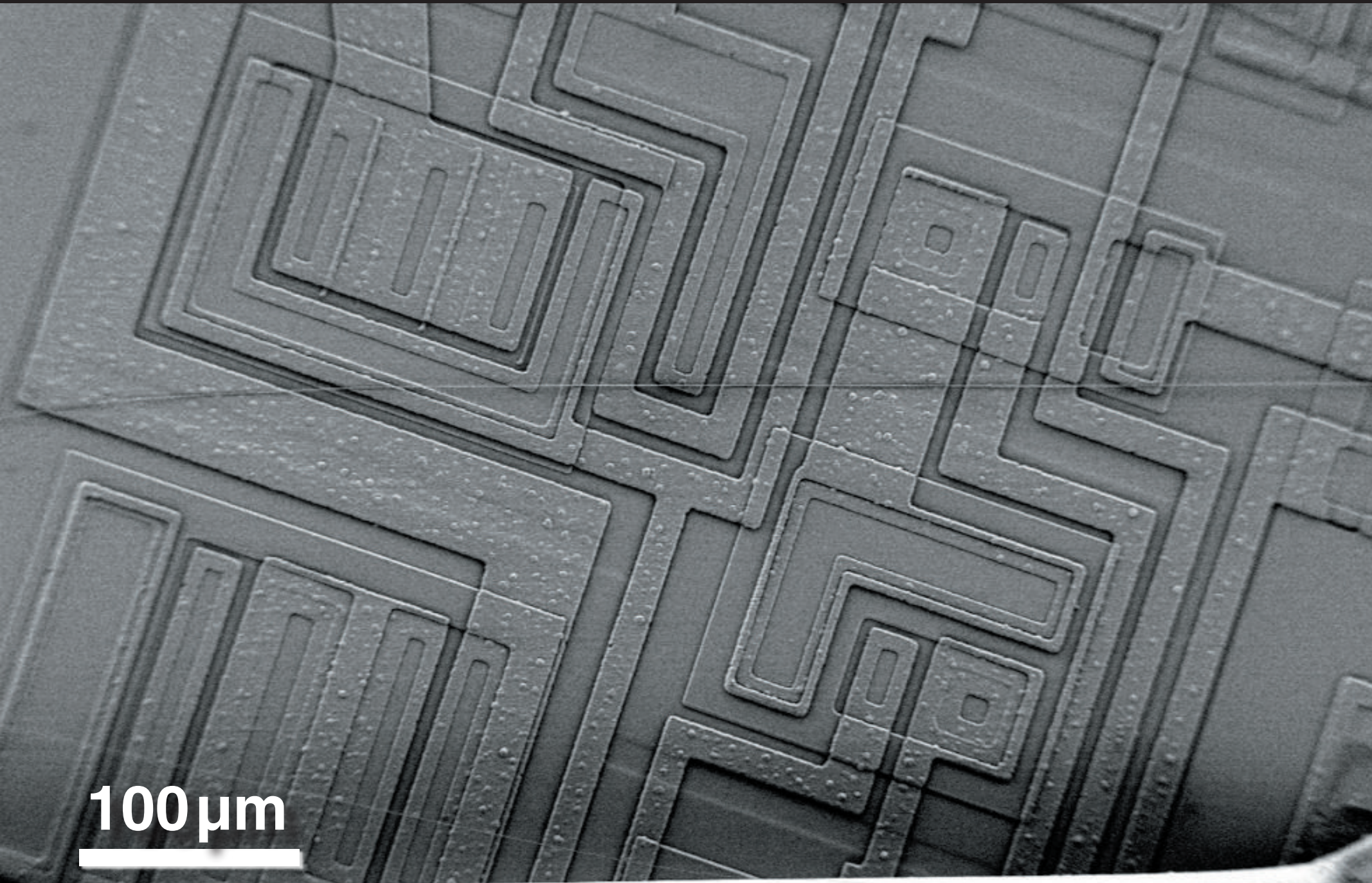


200 μm

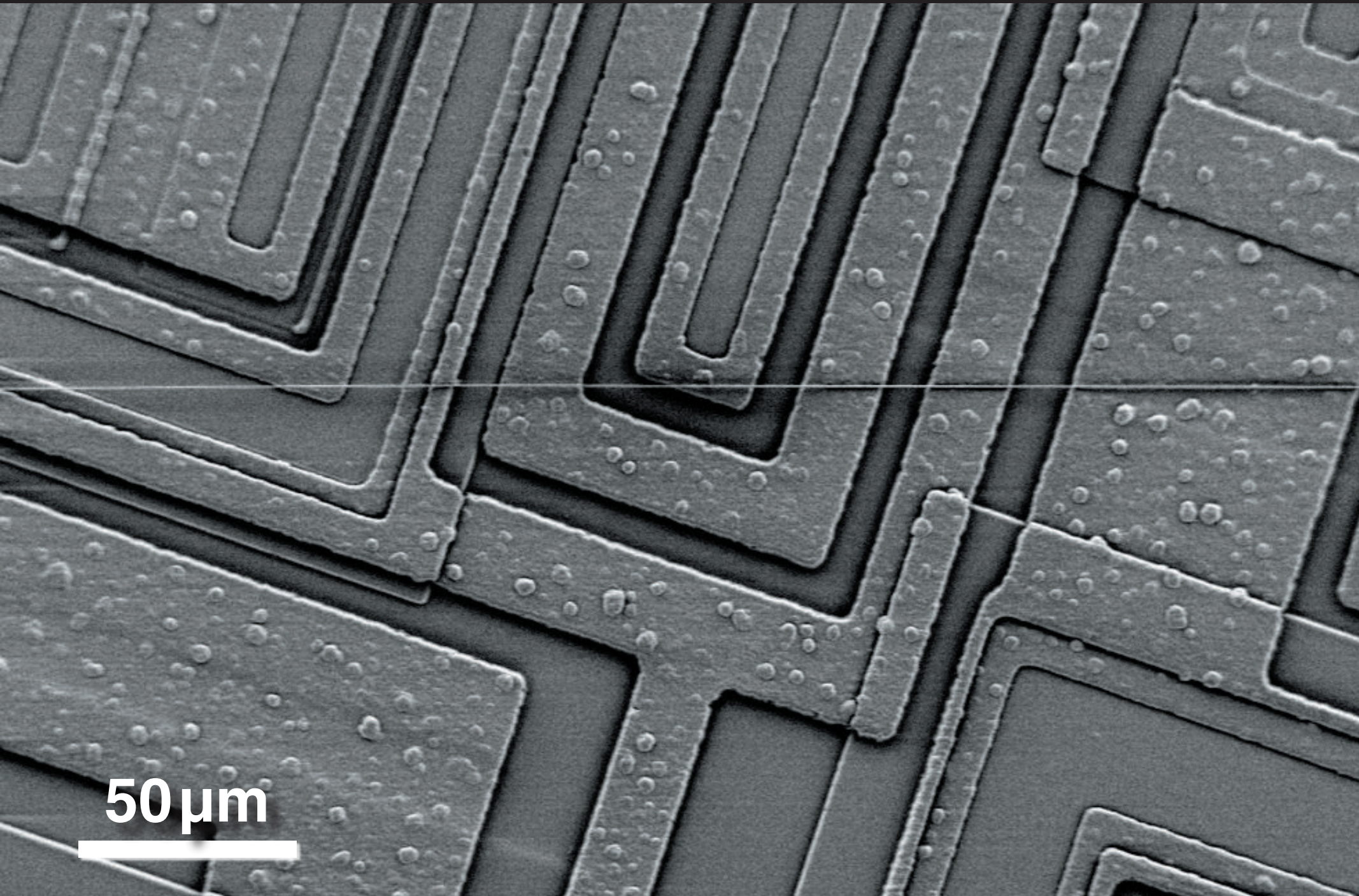
Nanowire fabrication



Nanowire fabrication

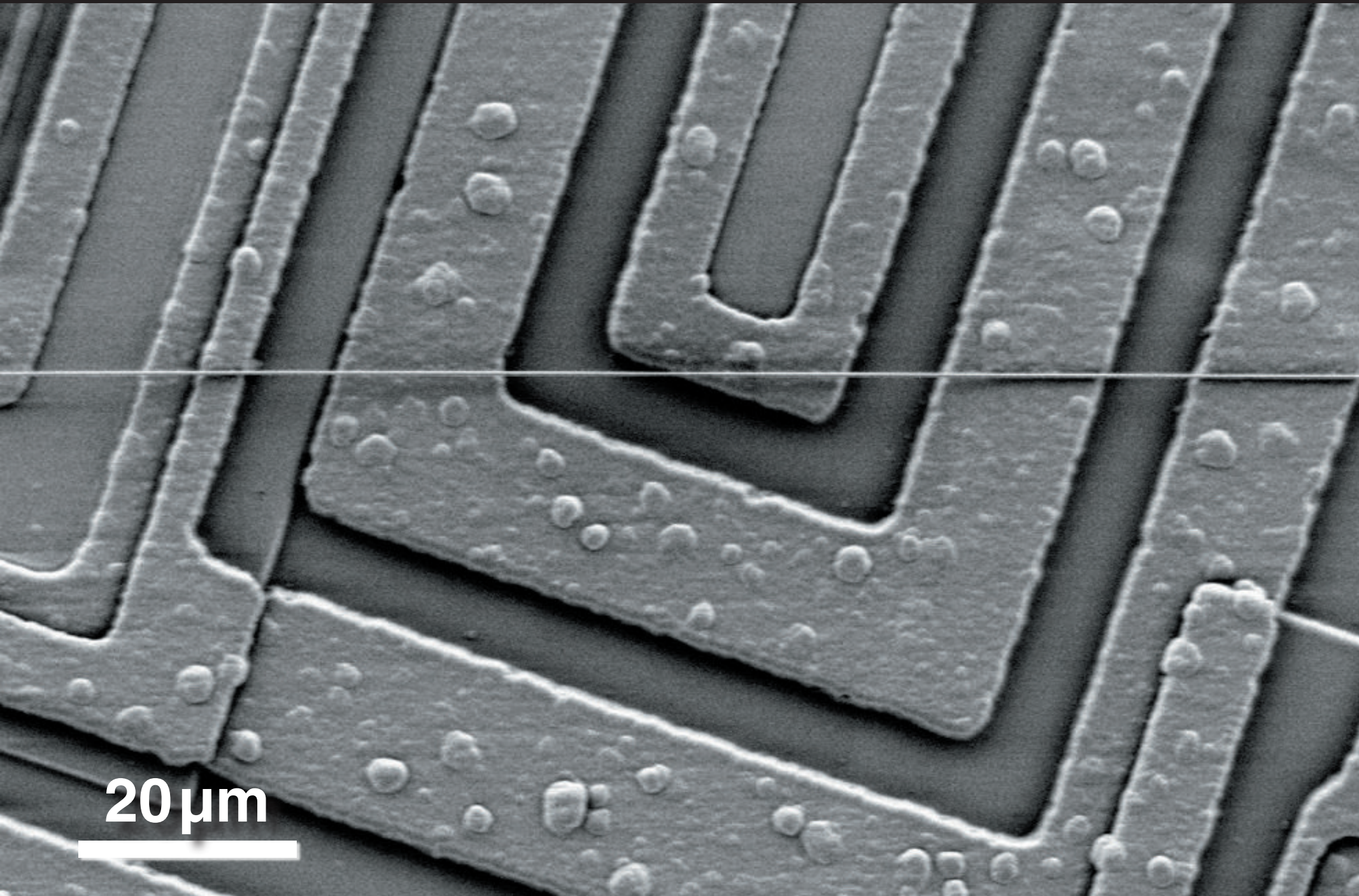


Nanowire fabrication

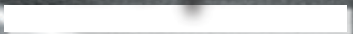


50 μm

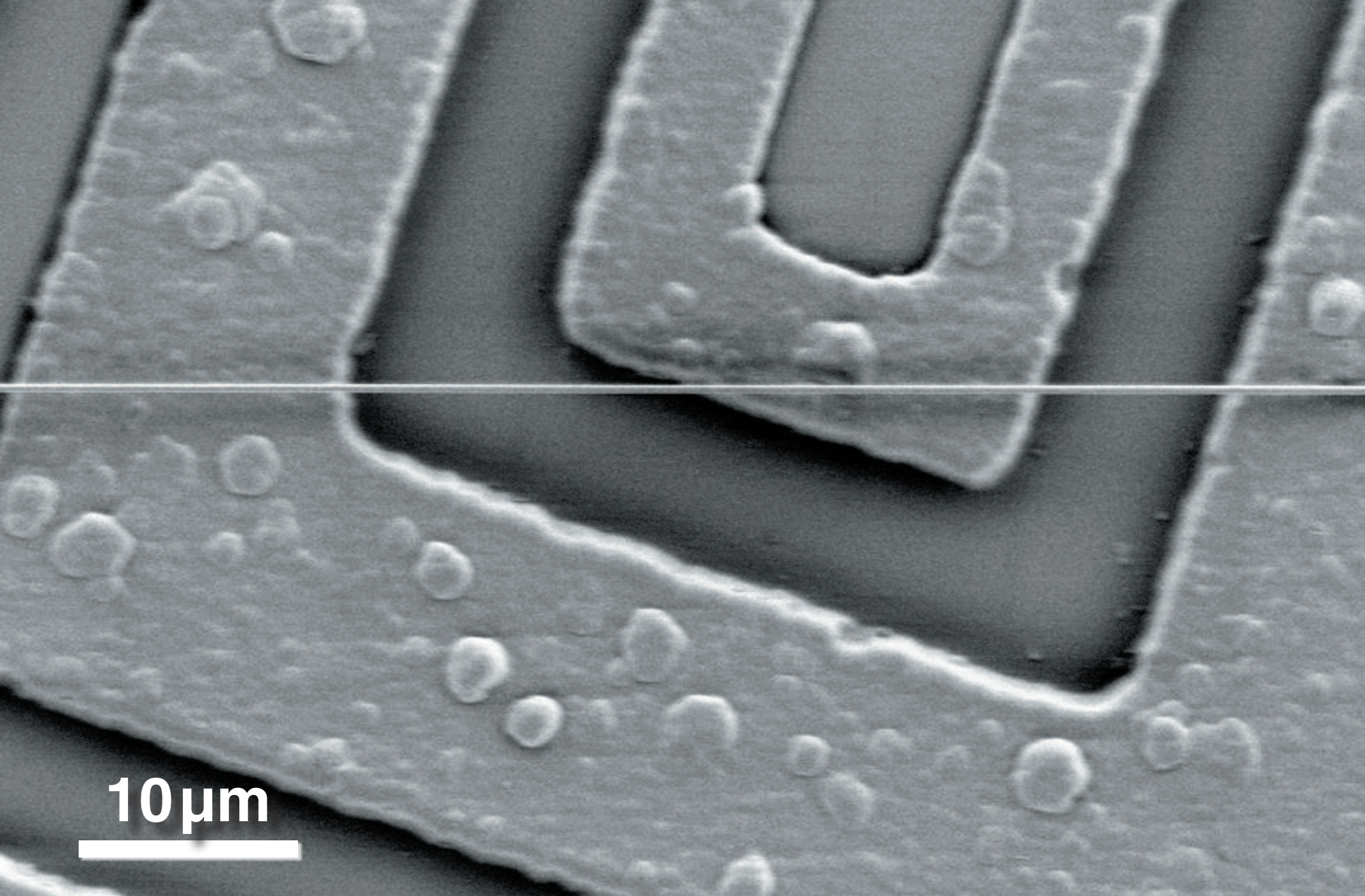
Nanowire fabrication



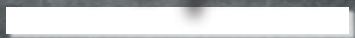
20 μm



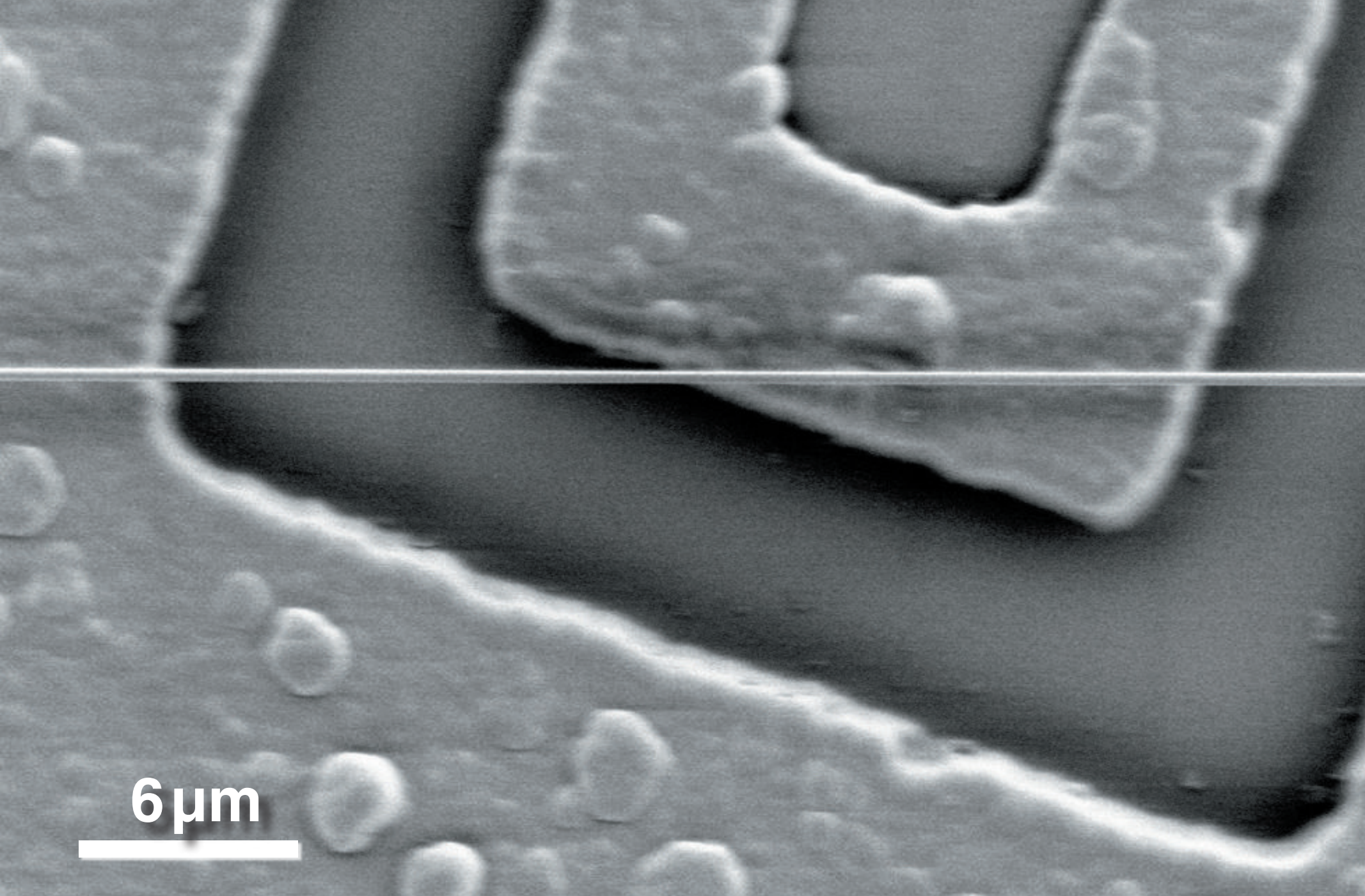
Nanowire fabrication



10 μm

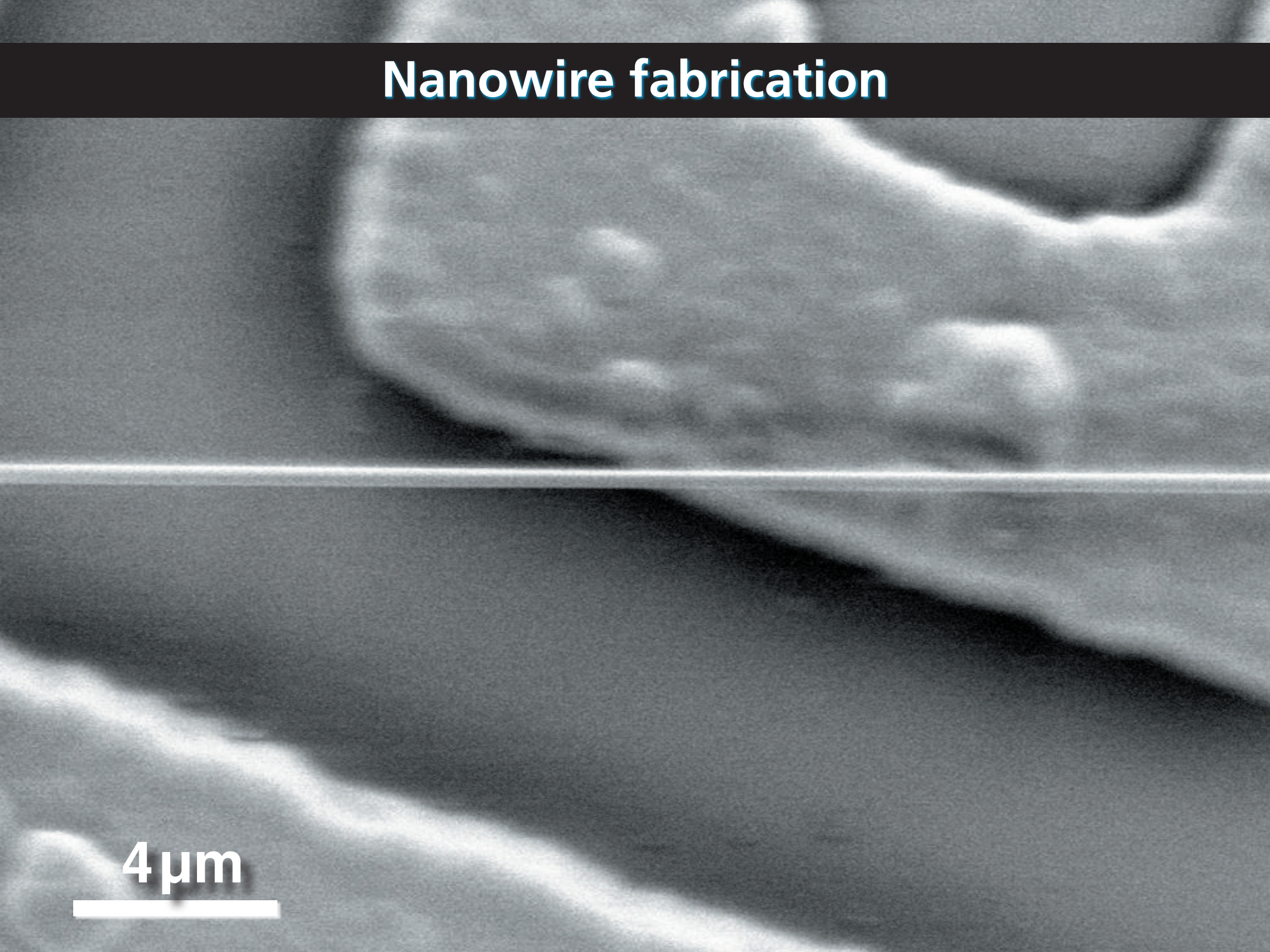


Nanowire fabrication



6 μm

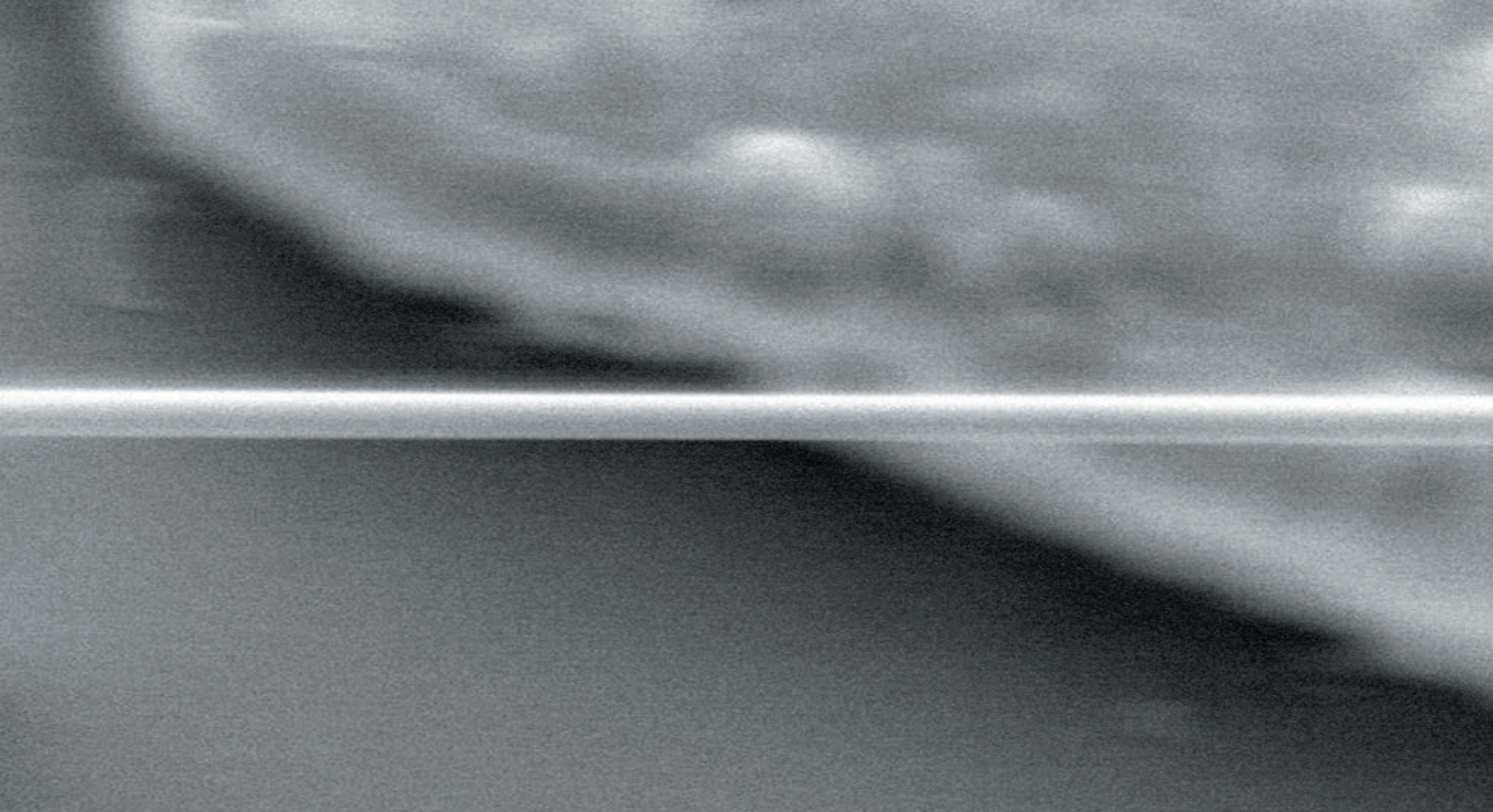
Nanowire fabrication



4 μm



Nanowire fabrication



2 μm



Nanowire fabrication

312 nm

A transmission electron micrograph (TEM) showing a single, long, cylindrical nanowire. The nanowire is oriented horizontally and has a uniform diameter. A vertical white line with a crossbar at the bottom is drawn across the center of the nanowire to indicate its diameter. The text "312 nm" is placed above this line. The background is dark and grainy, typical of a TEM image.

1 μm

A white horizontal scale bar located in the bottom left corner of the image. The text "1 μm" is positioned above the bar.

Waveguiding

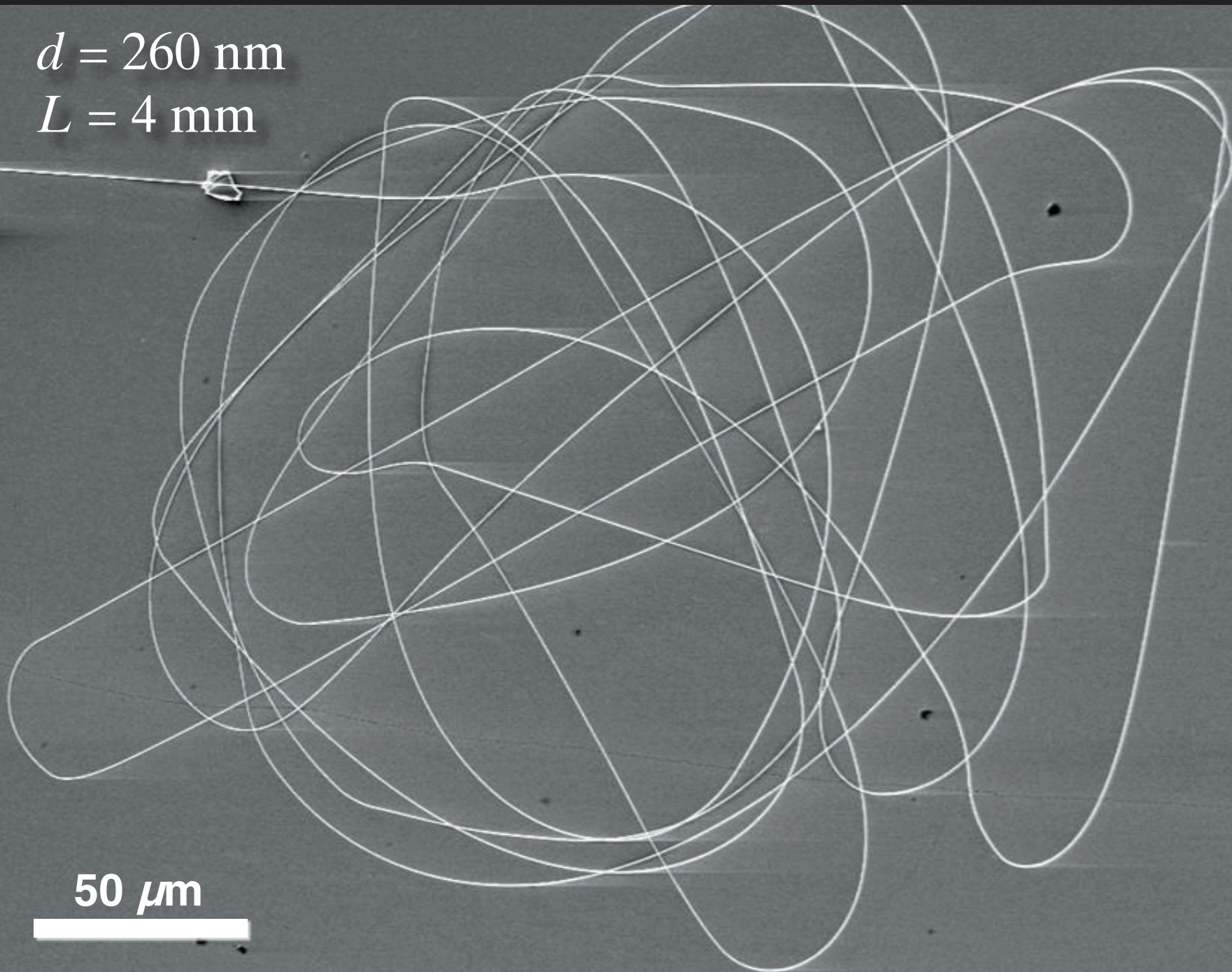
Specifications

diameter D :	down to 20 nm
length L :	up to 90 mm
aspect ratio D/L :	up to 10^6
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nanowire fabrication

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50 μm

Nanowire fabrication

240-nm wire

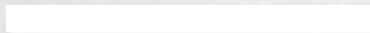
200 nm



Nanowire fabrication

RMS roughness < 0.5 nm

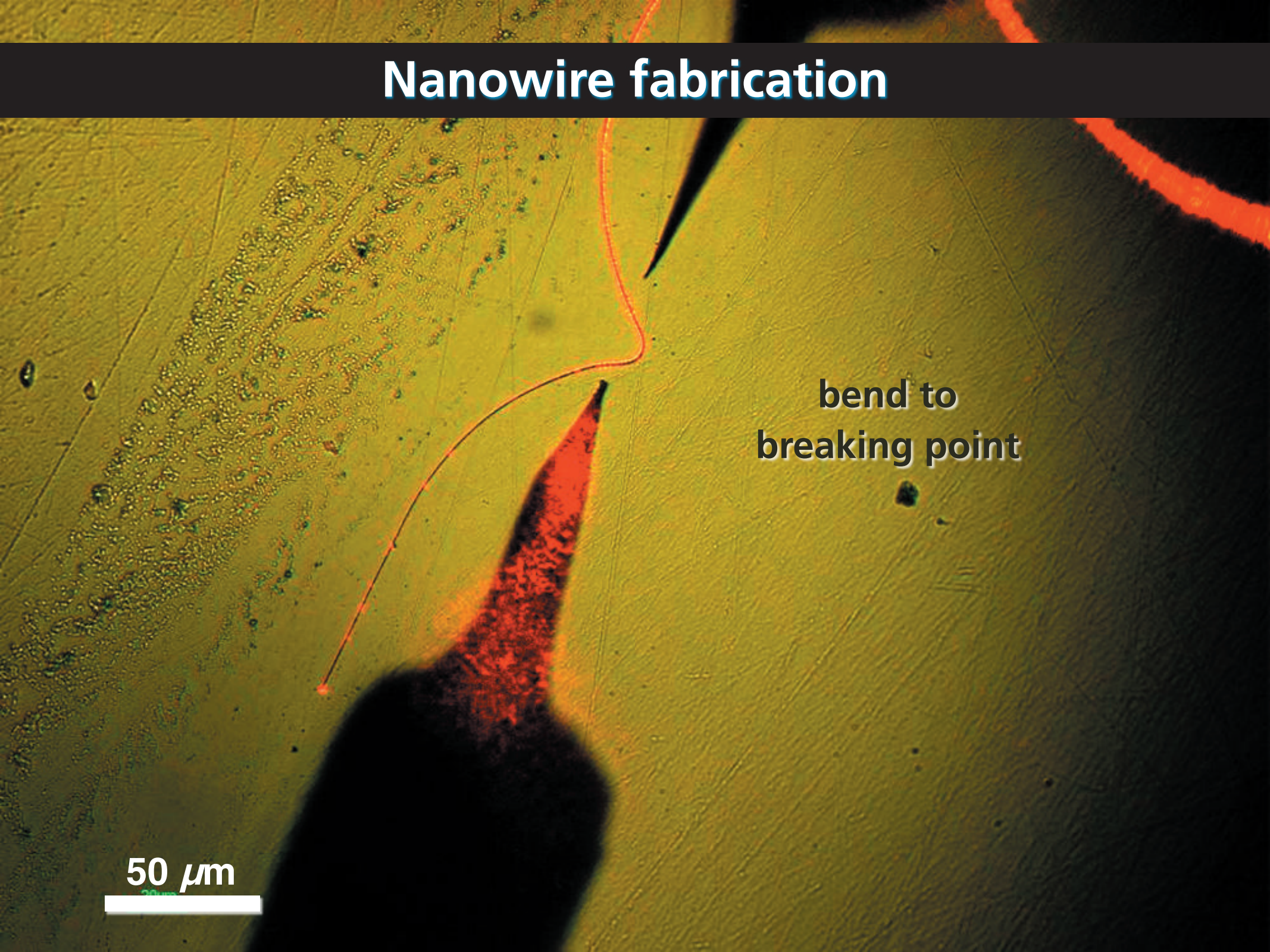
20 nm



Nanowire fabrication

bend to
breaking point

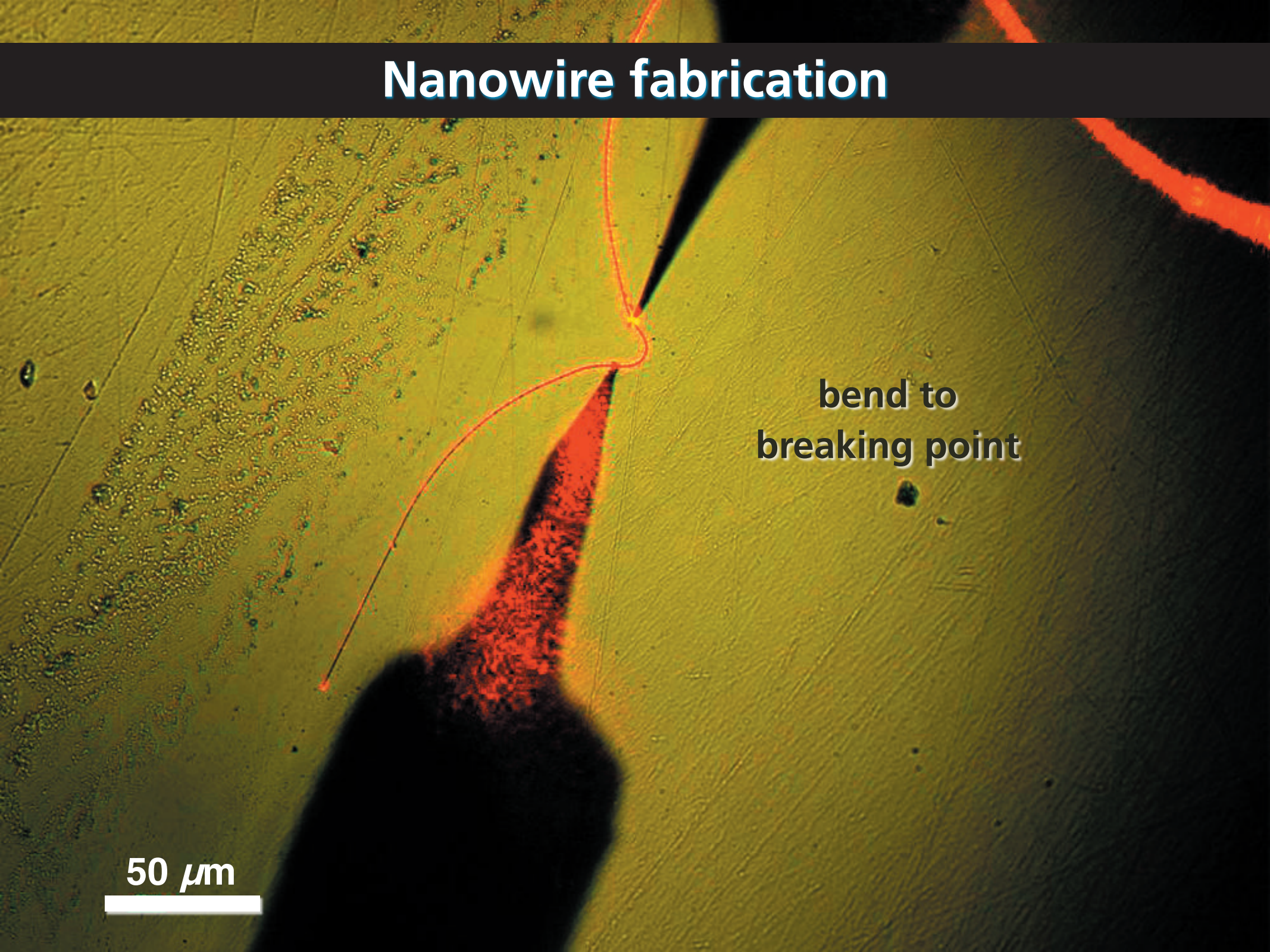
50 μm



Nanowire fabrication

bend to
breaking point

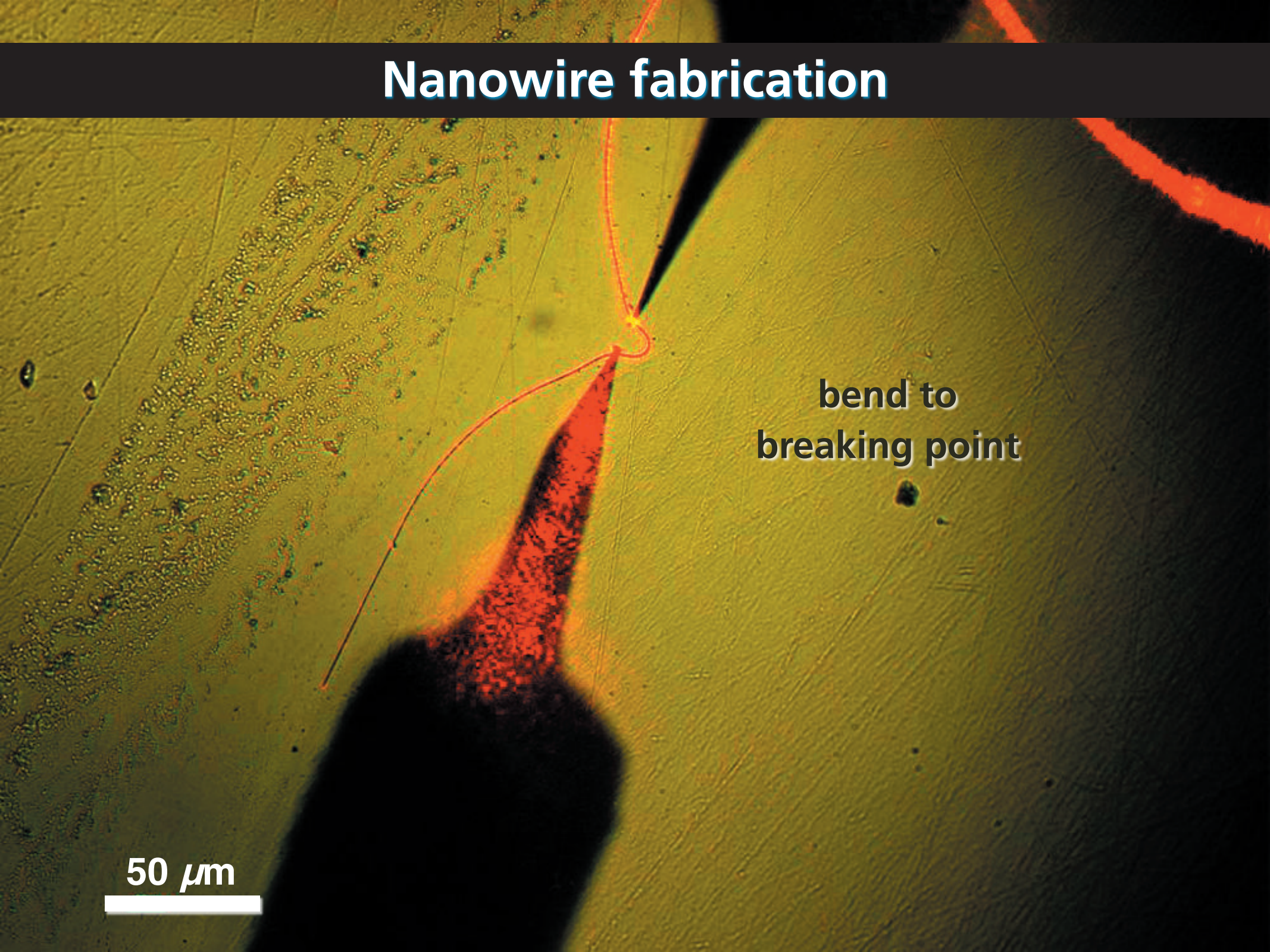
50 μm



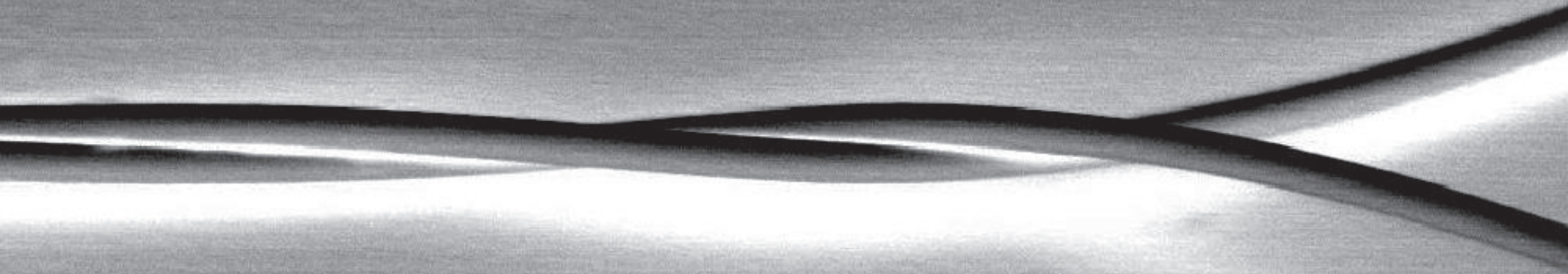
Nanowire fabrication

bend to
breaking point

50 μm



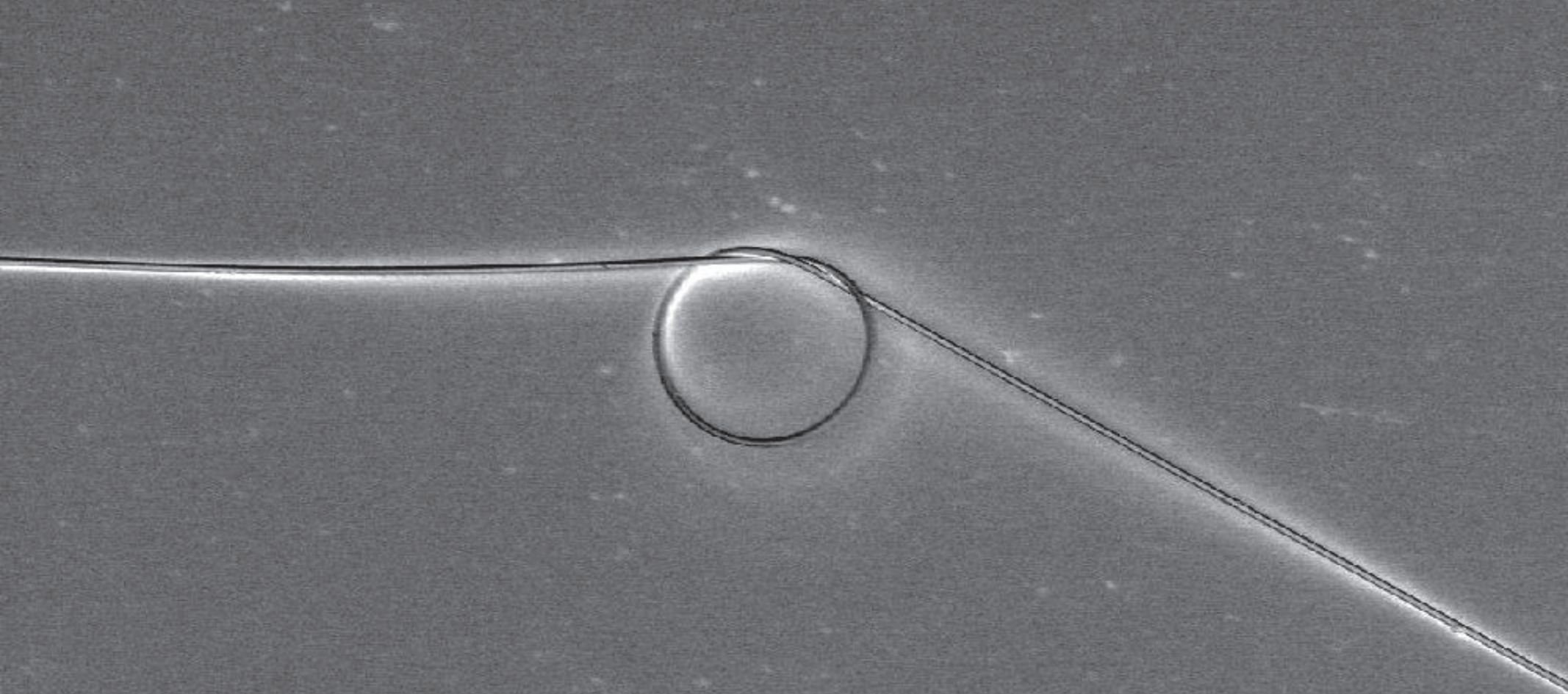
Nanowire fabrication



2 μm



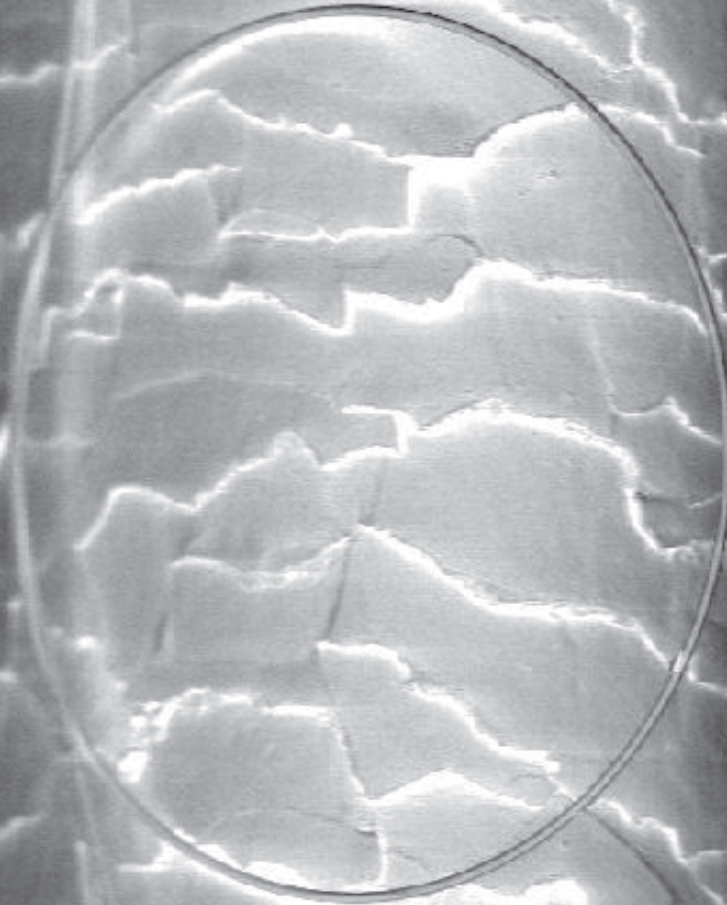
Nanowire fabrication



20 μm



Nanowire fabrication



20 μm

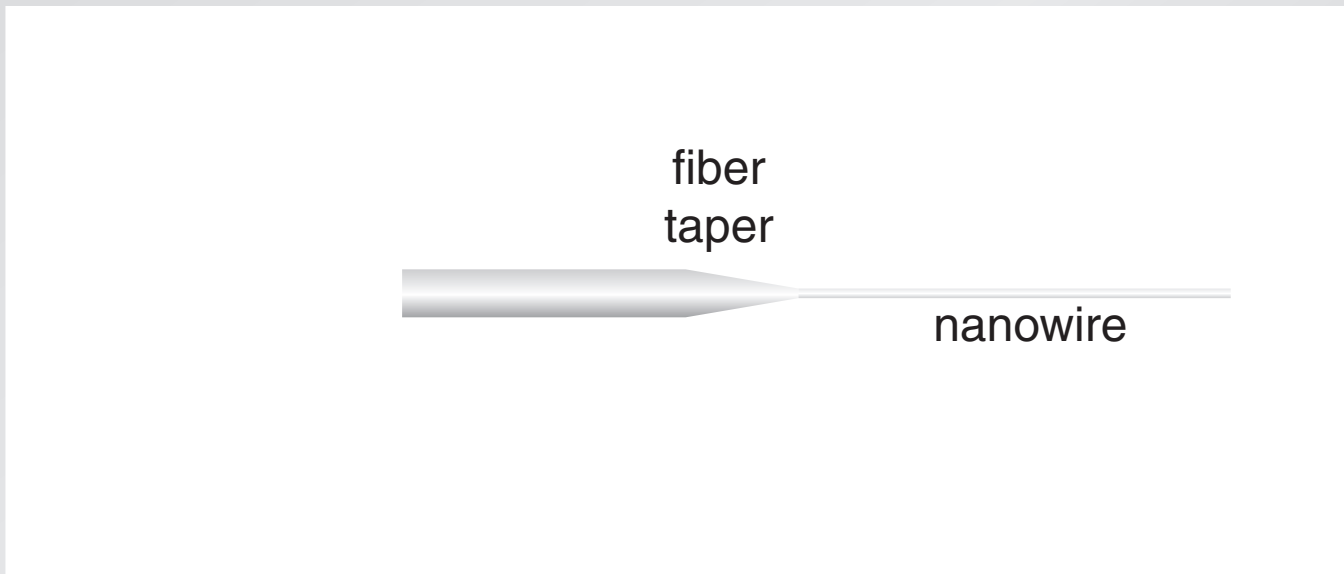


Outline

- waveguiding
- nanowire fabrication
- optical properties

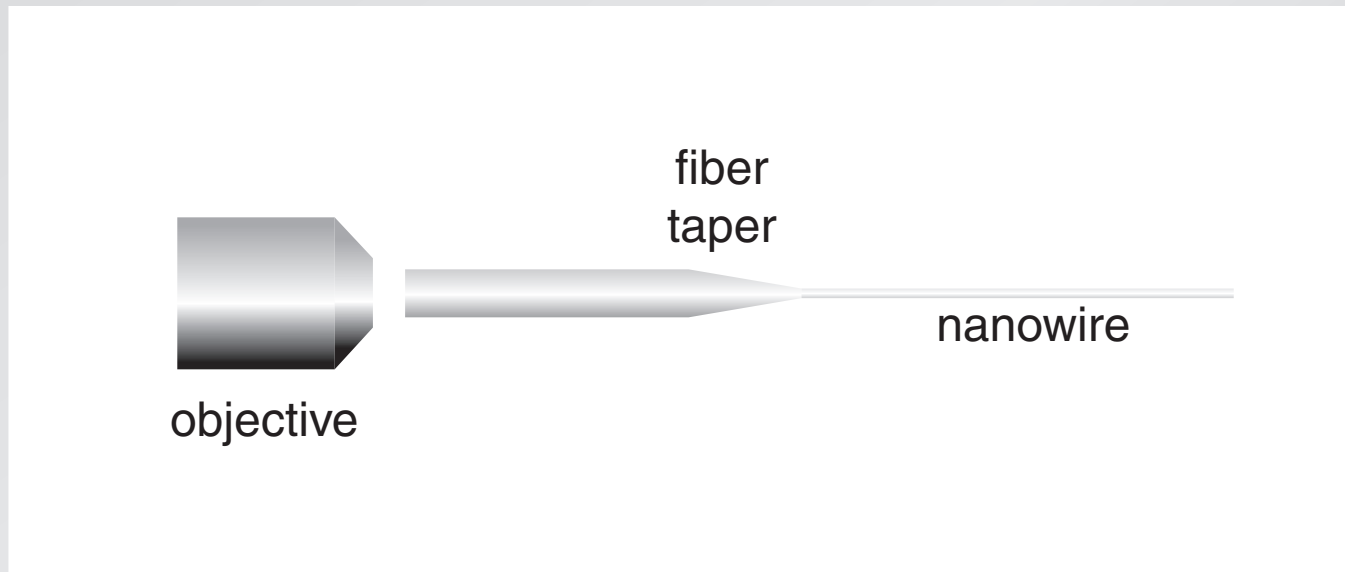
Optical properties

coupling light into nanowires



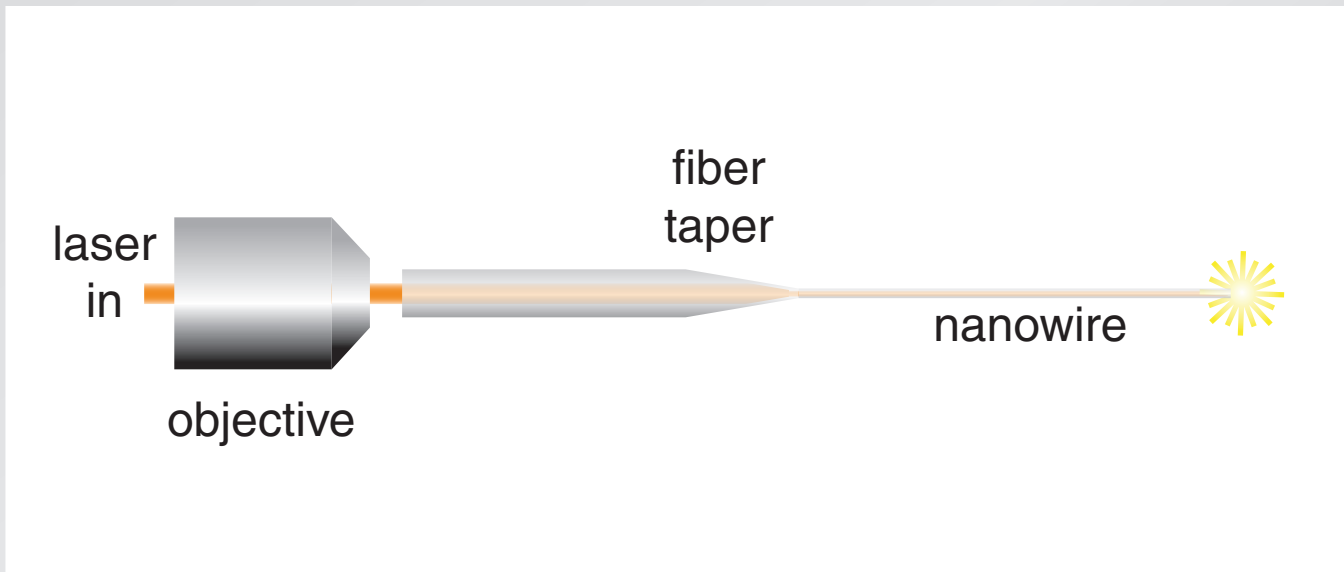
Optical properties

coupling light into nanowires



Optical properties

coupling light into nanowires



Optical properties

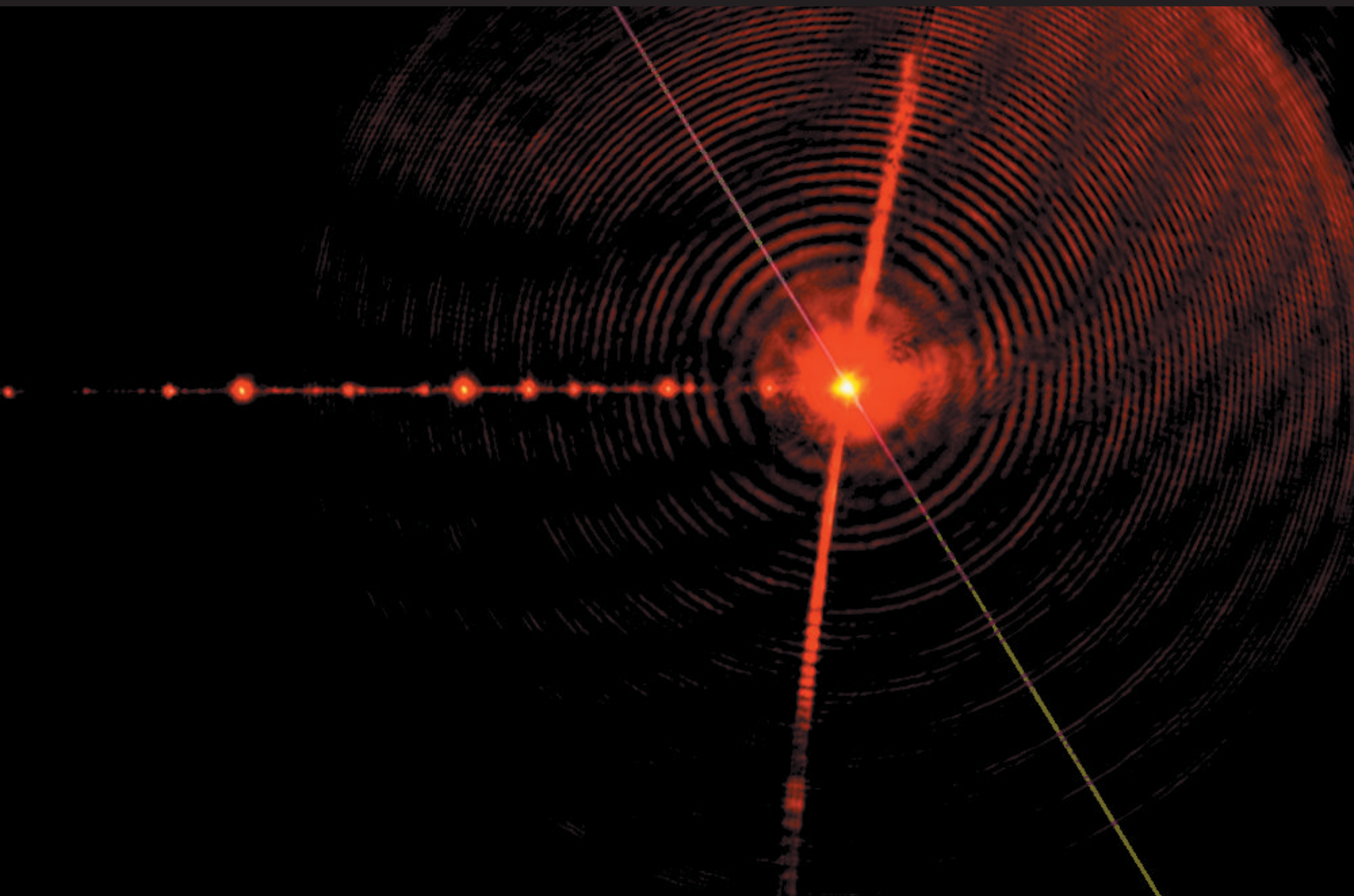
280-nm nanowire



360 nm

450 nm

Optical properties

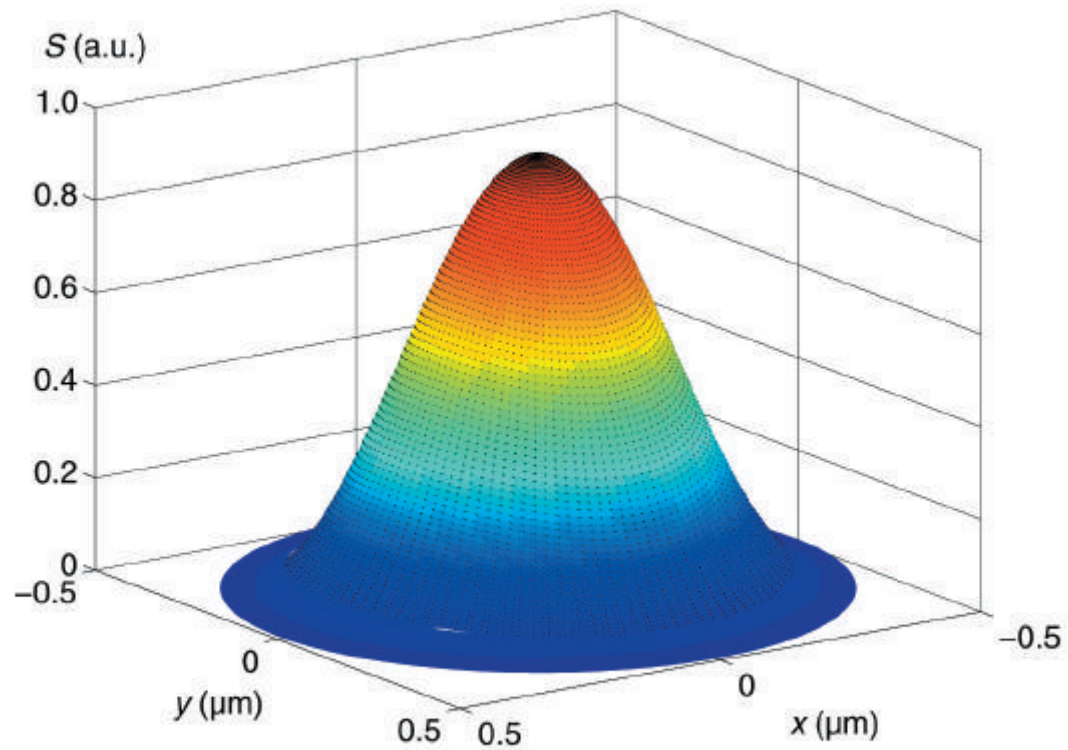


Optical properties



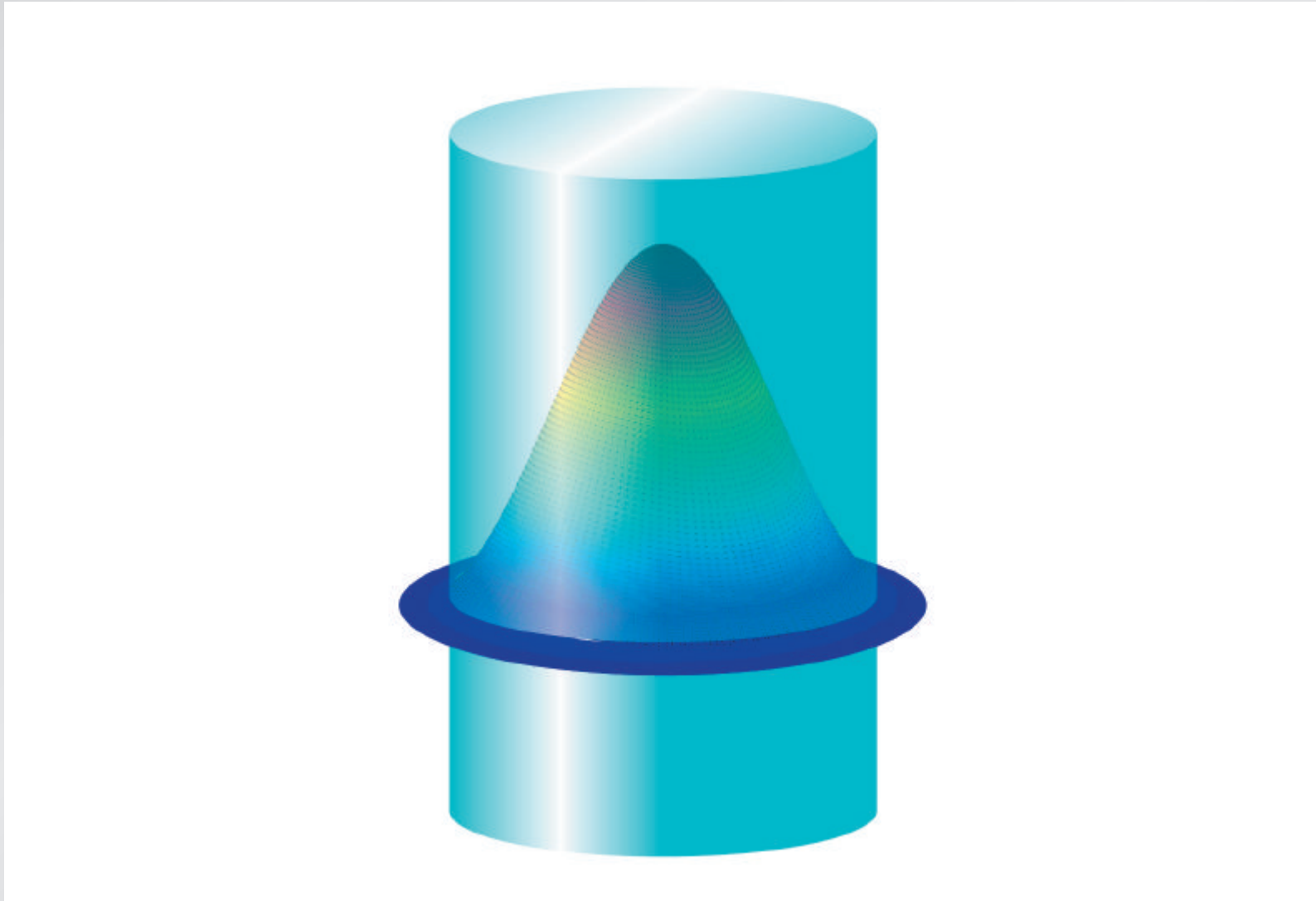
Optical properties

Poynting vector profile for 800-nm nanowire



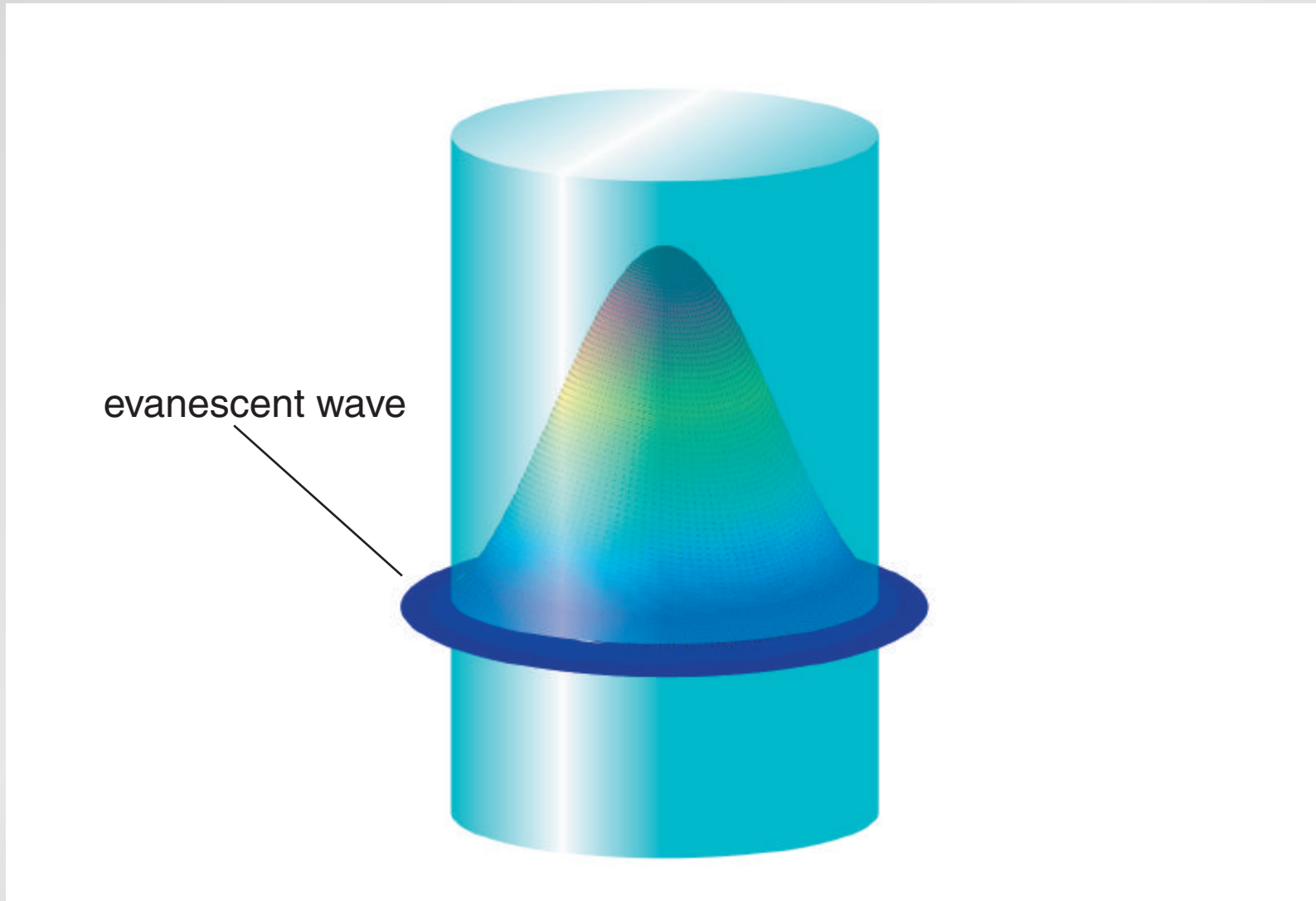
Optical properties

Poynting vector profile for 800-nm nanowire



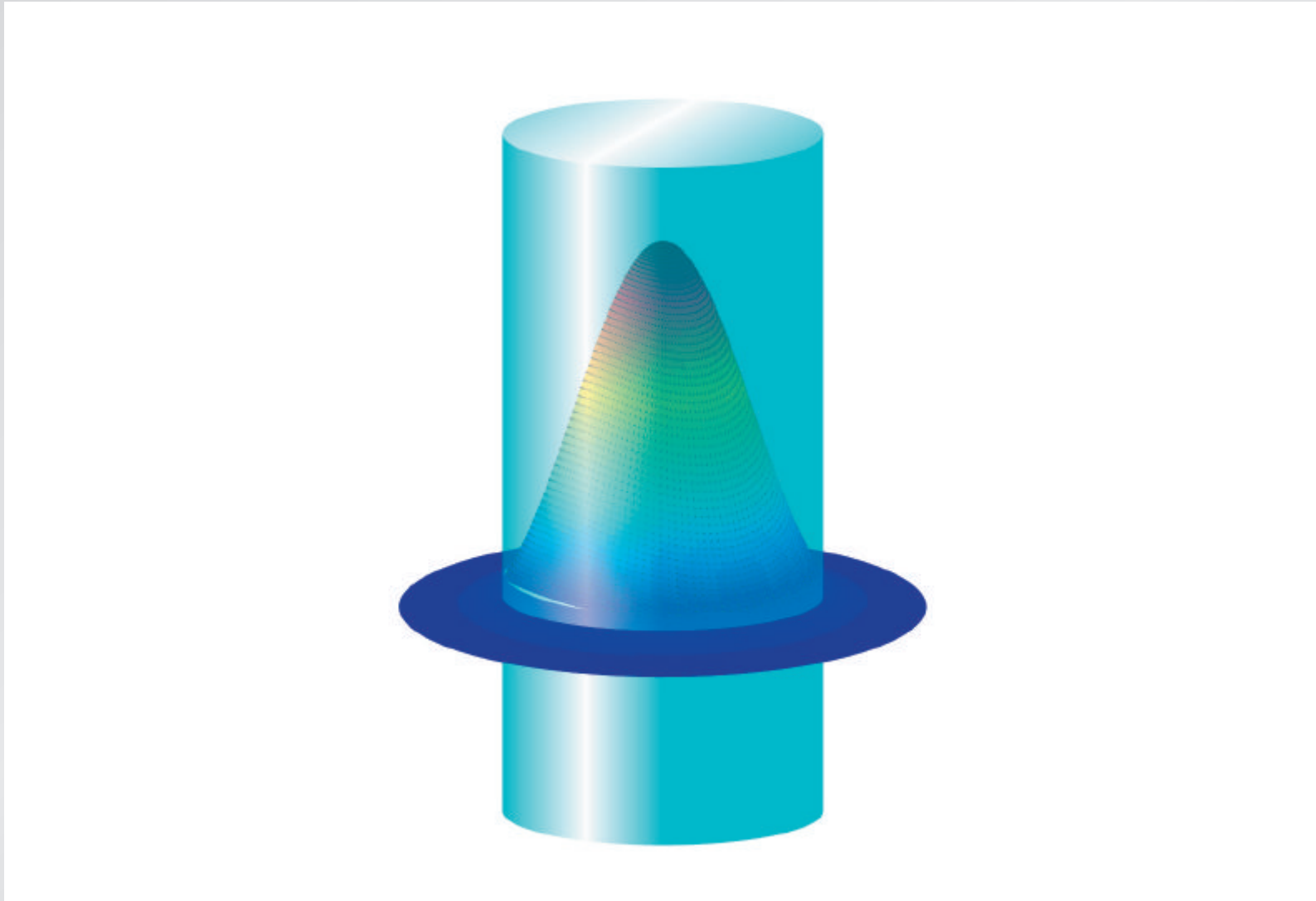
Optical properties

Poynting vector profile for 800-nm nanowire



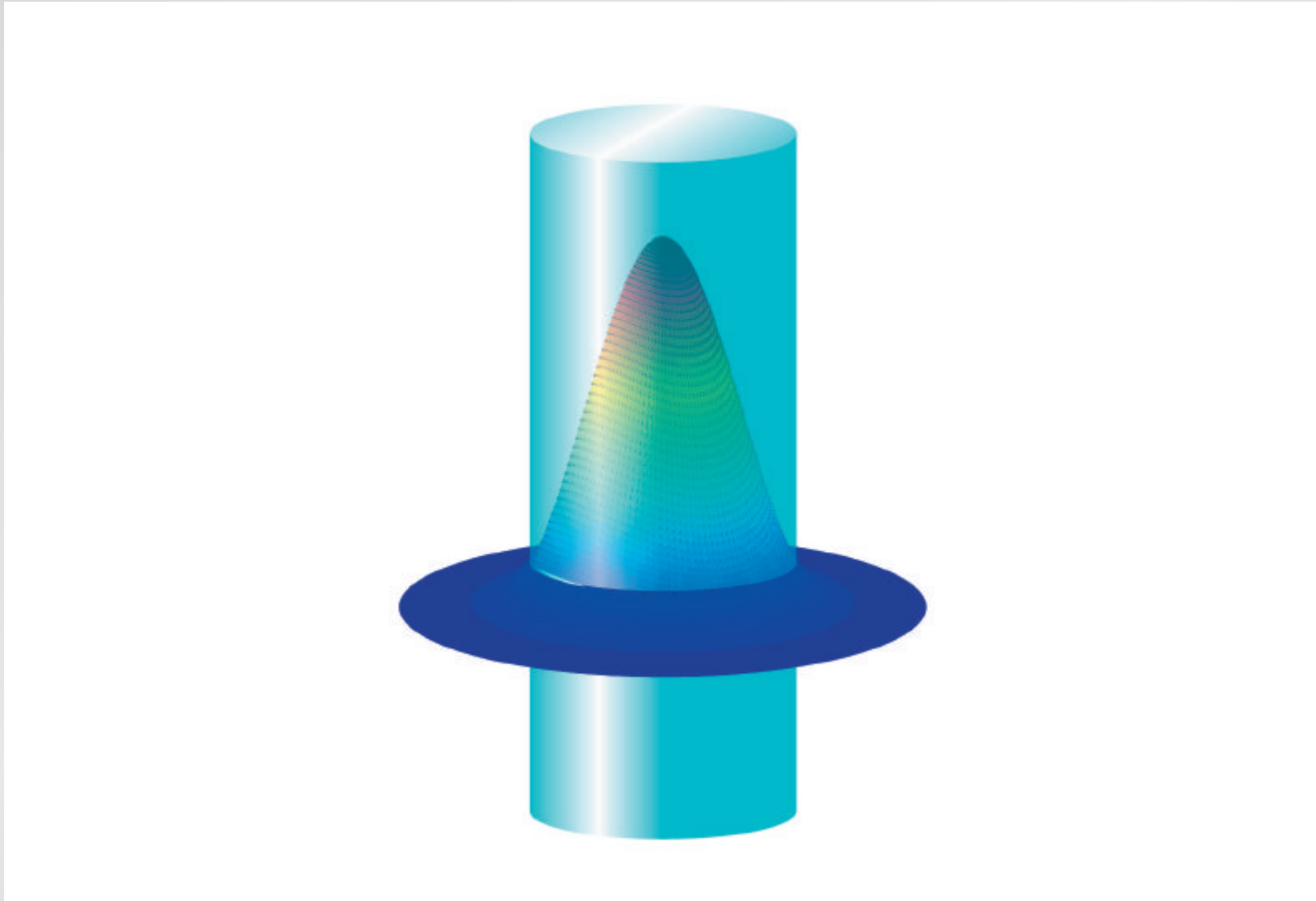
Optical properties

Poynting vector profile for 600-nm nanowire



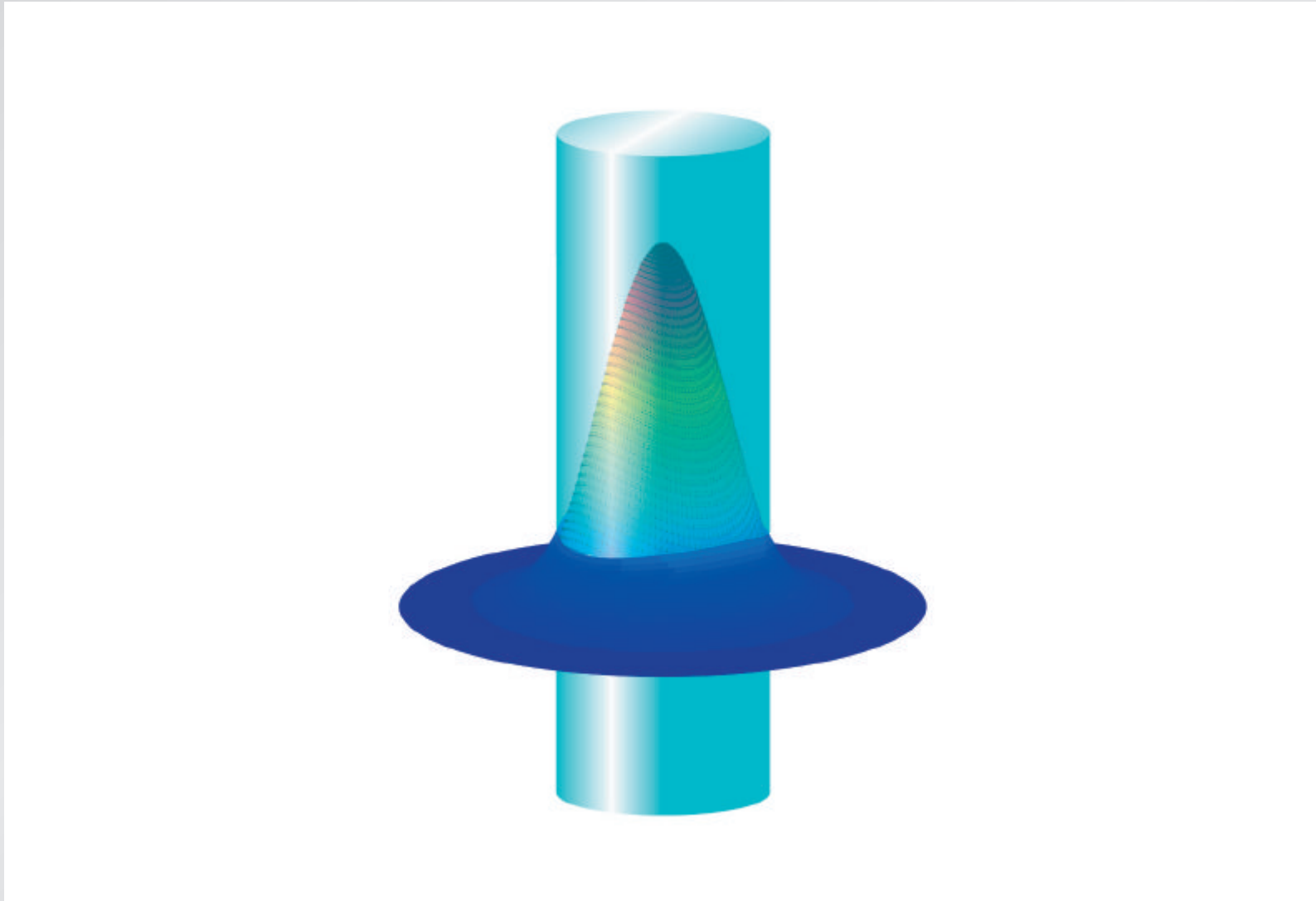
Optical properties

Poynting vector profile for 500-nm nanowire



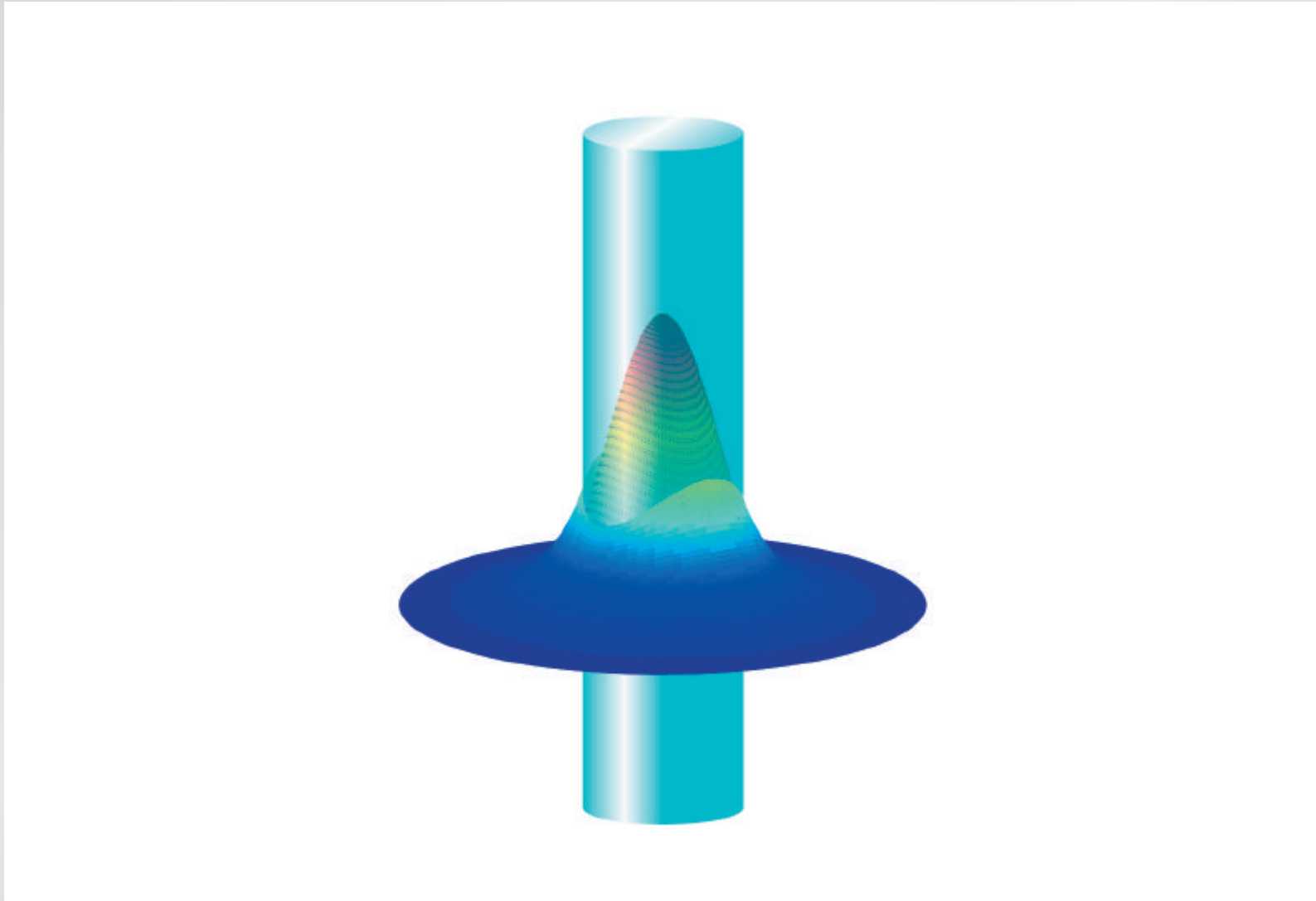
Optical properties

Poynting vector profile for 400-nm nanowire



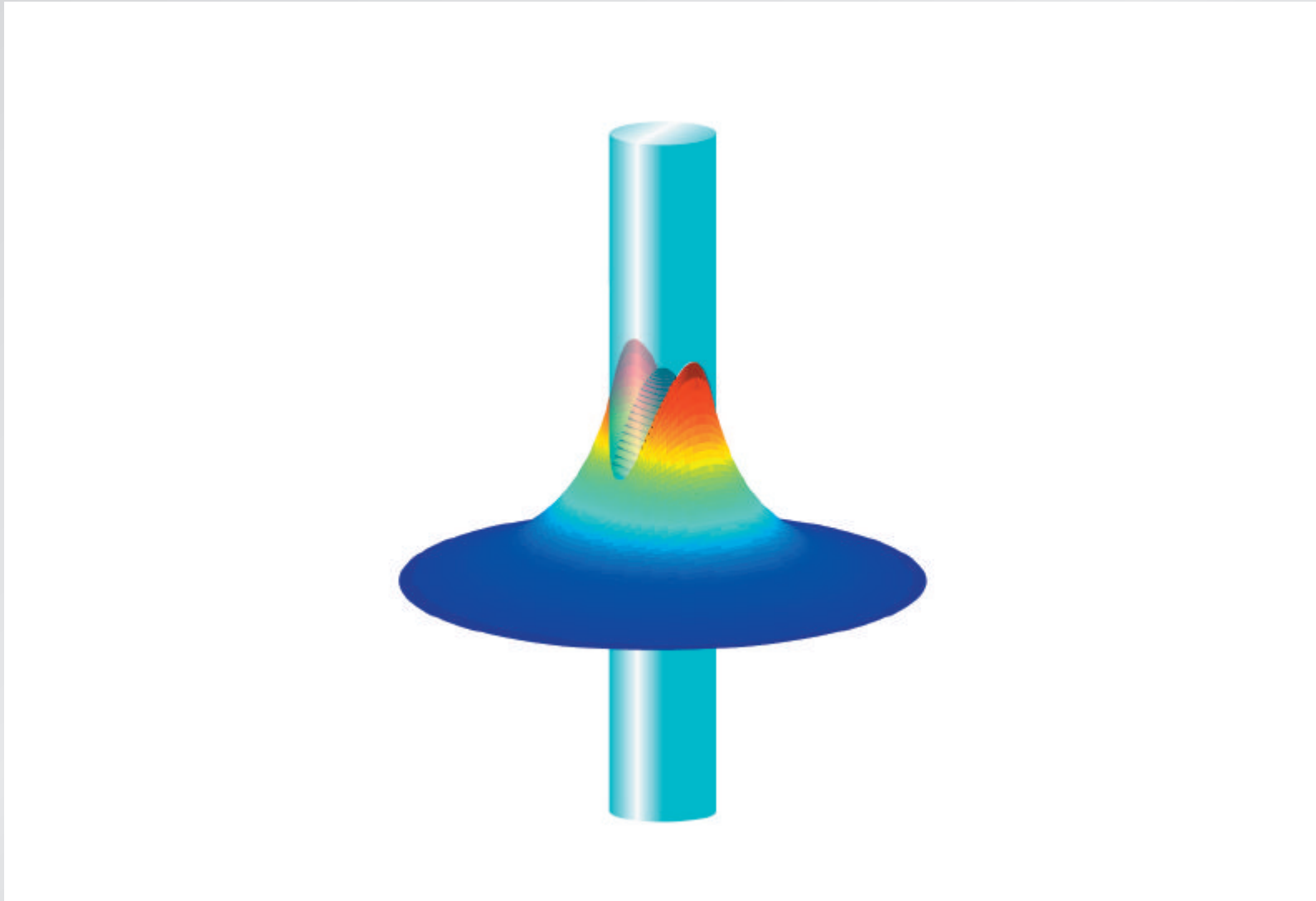
Optical properties

Poynting vector profile for 300-nm nanowire



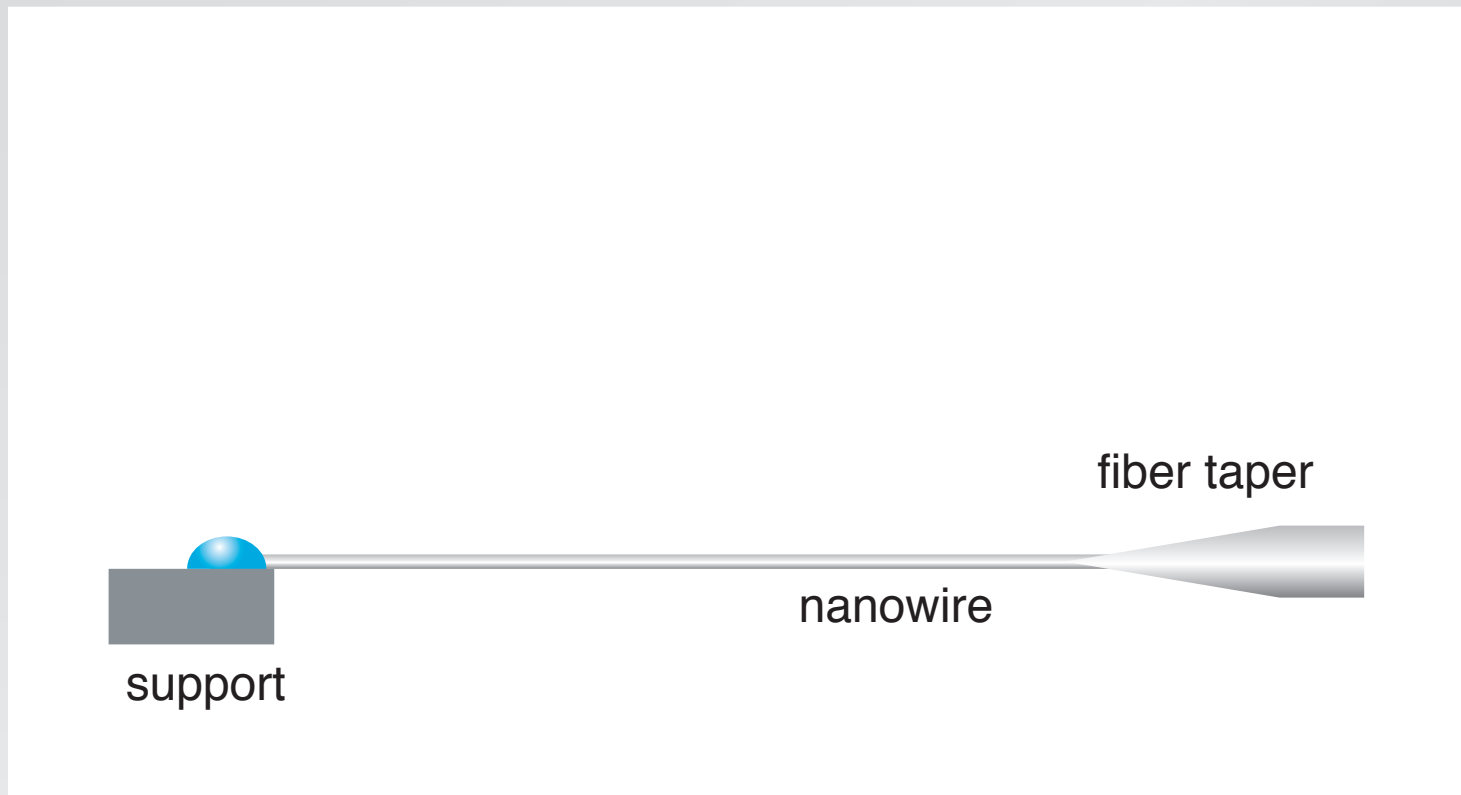
Optical properties

Poynting vector profile for 200-nm nanowire



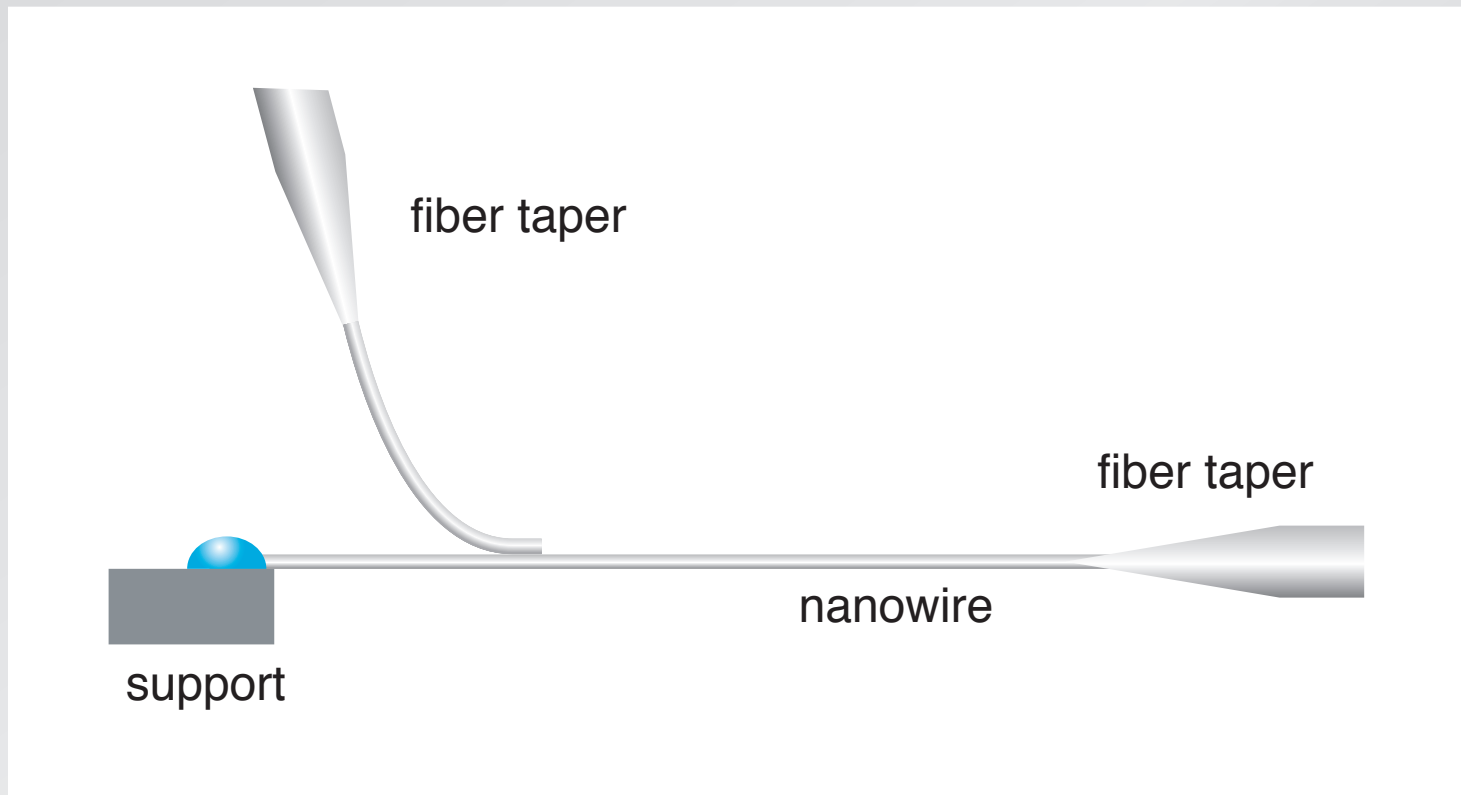
Optical properties

coupling light between nanowires



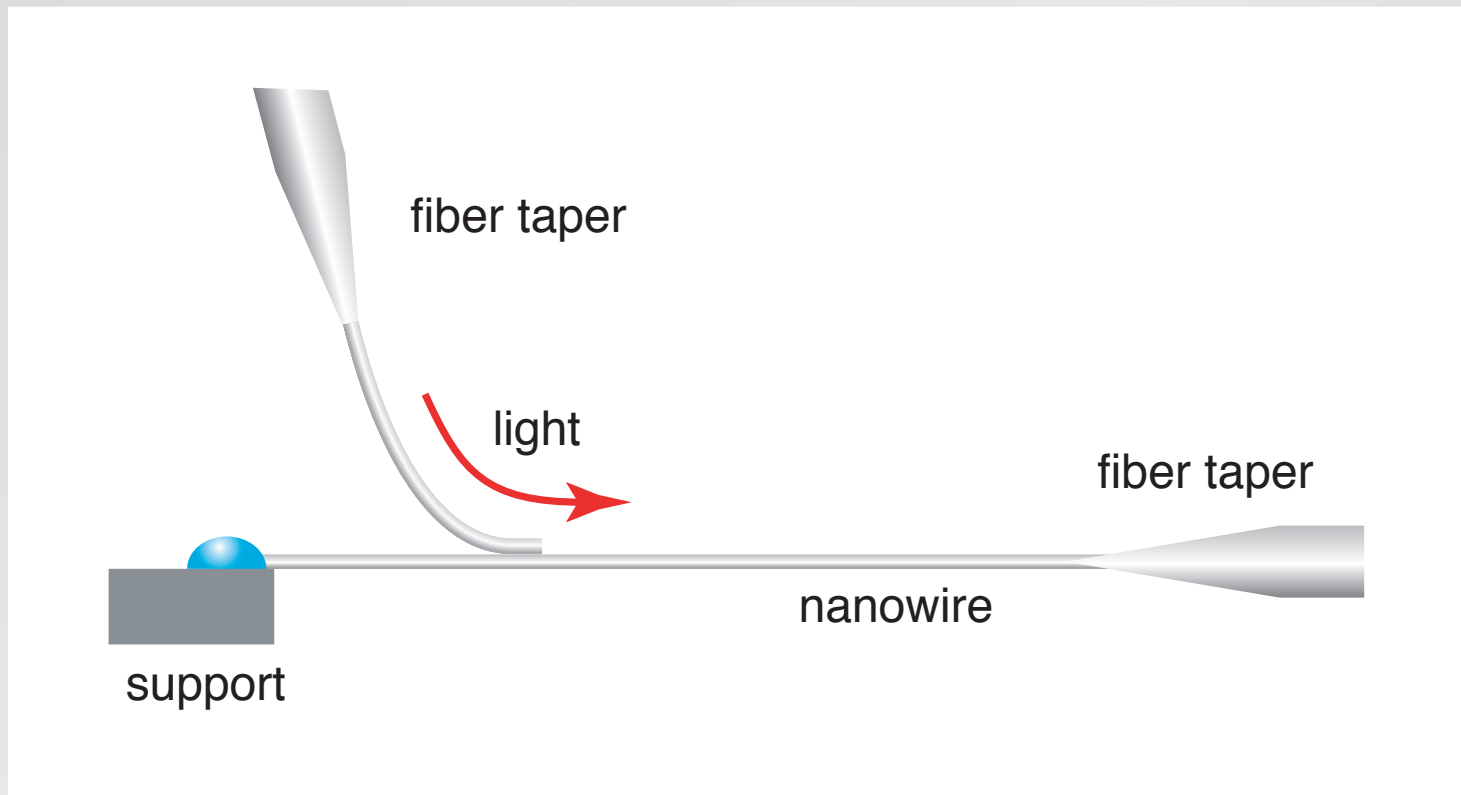
Optical properties

coupling light between nanowires

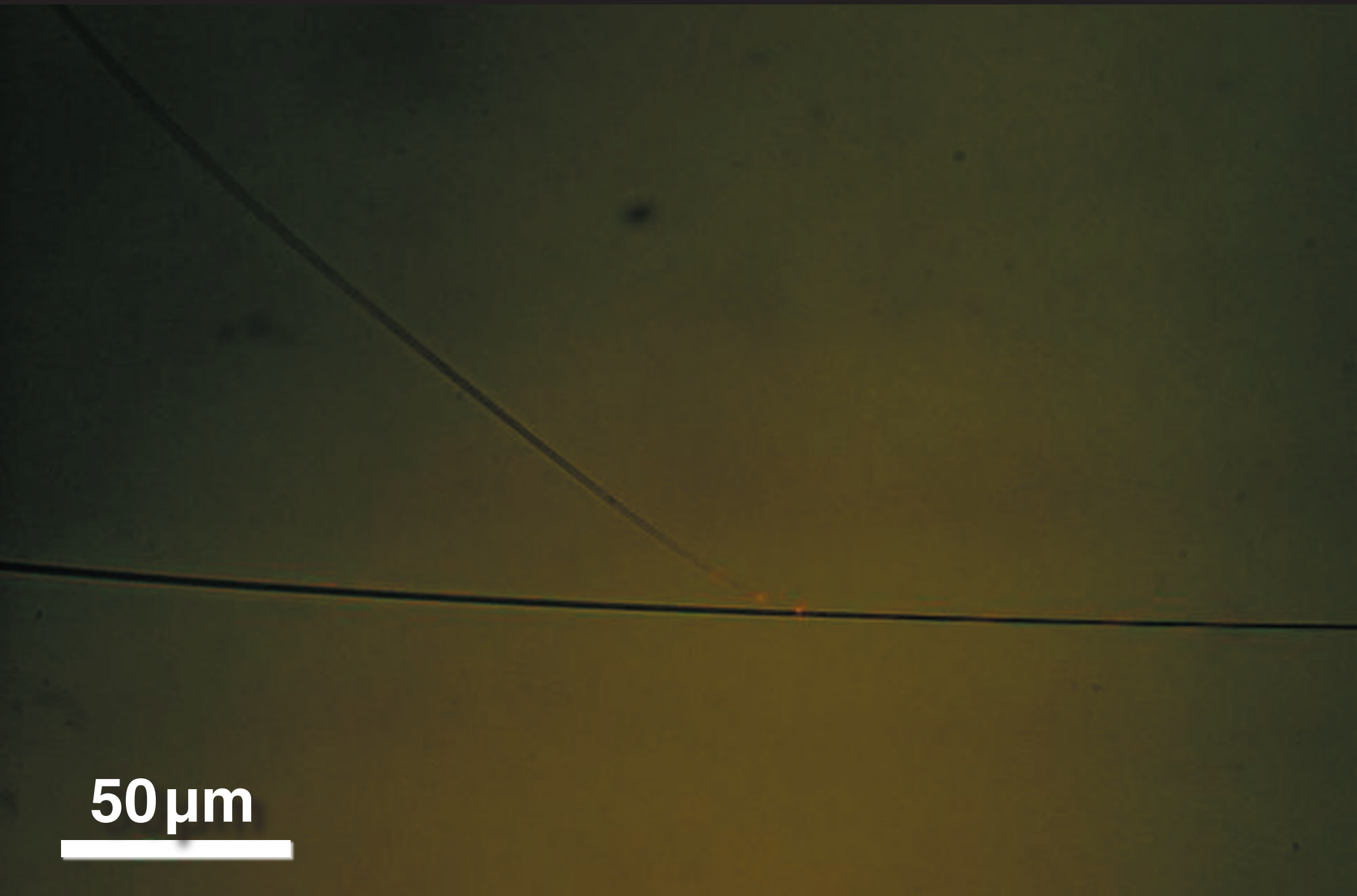


Optical properties

coupling light between nanowires



Optical properties

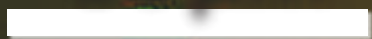


50 μm

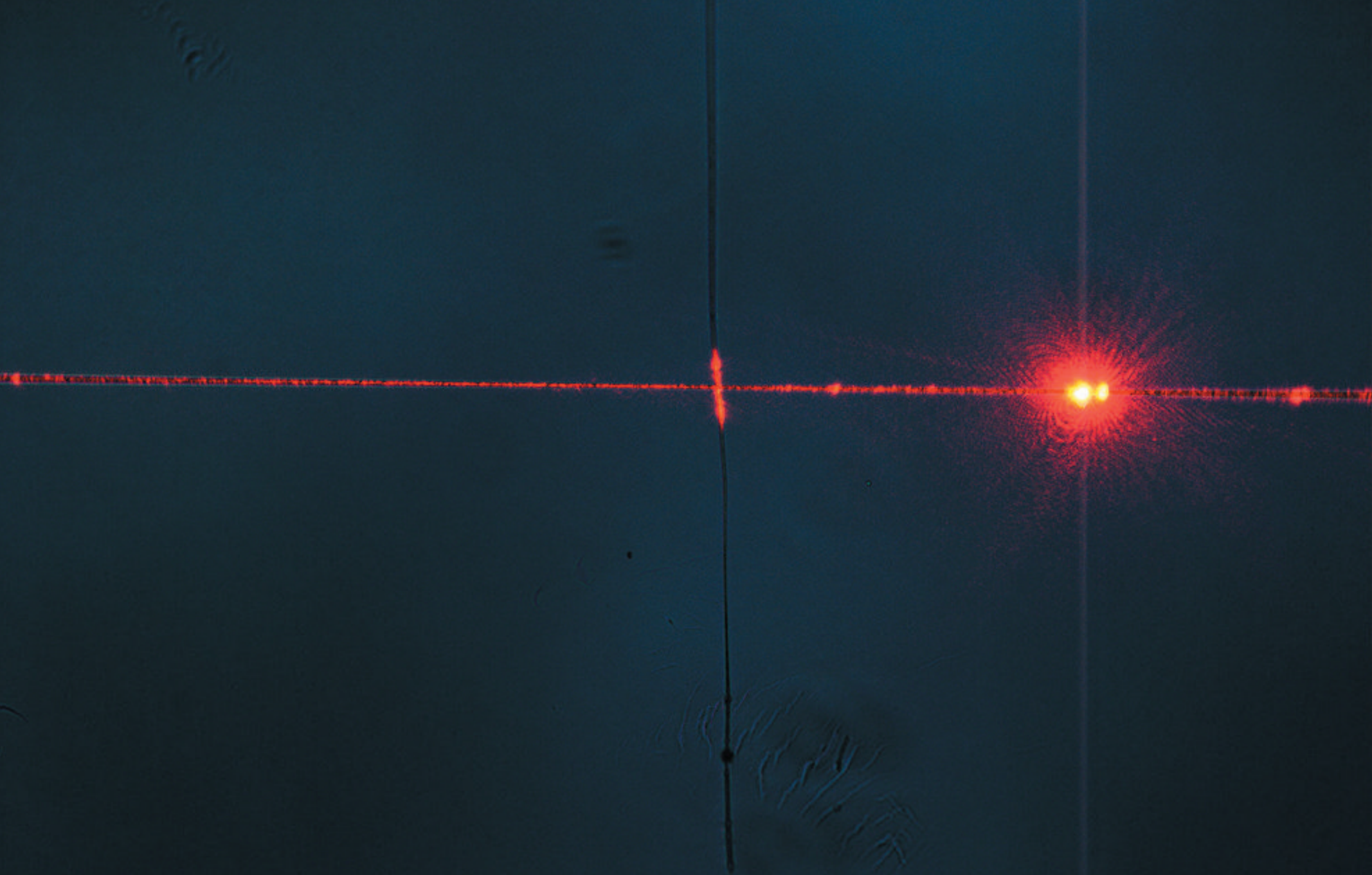
Optical properties



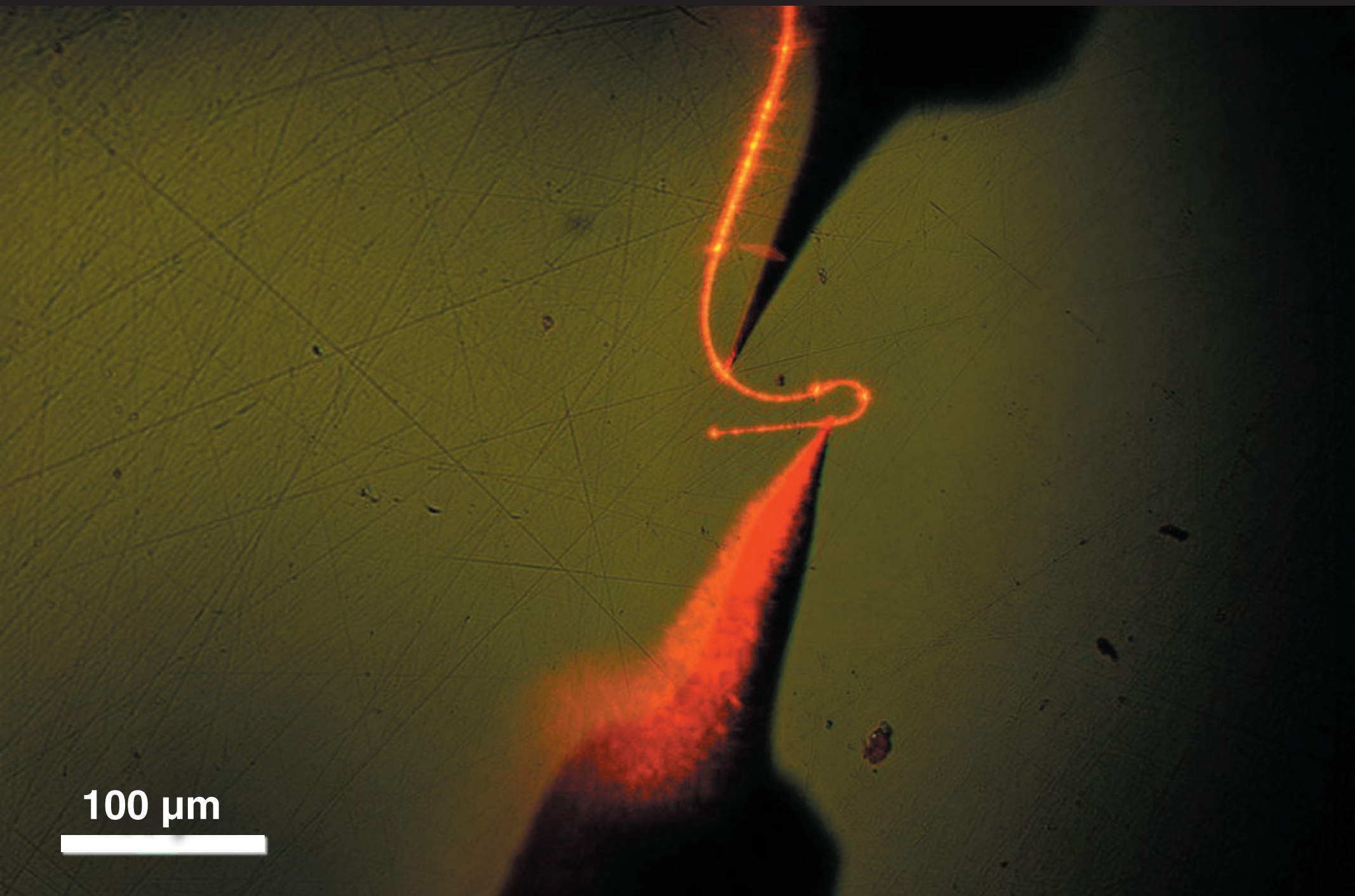
50 μm



Optical properties

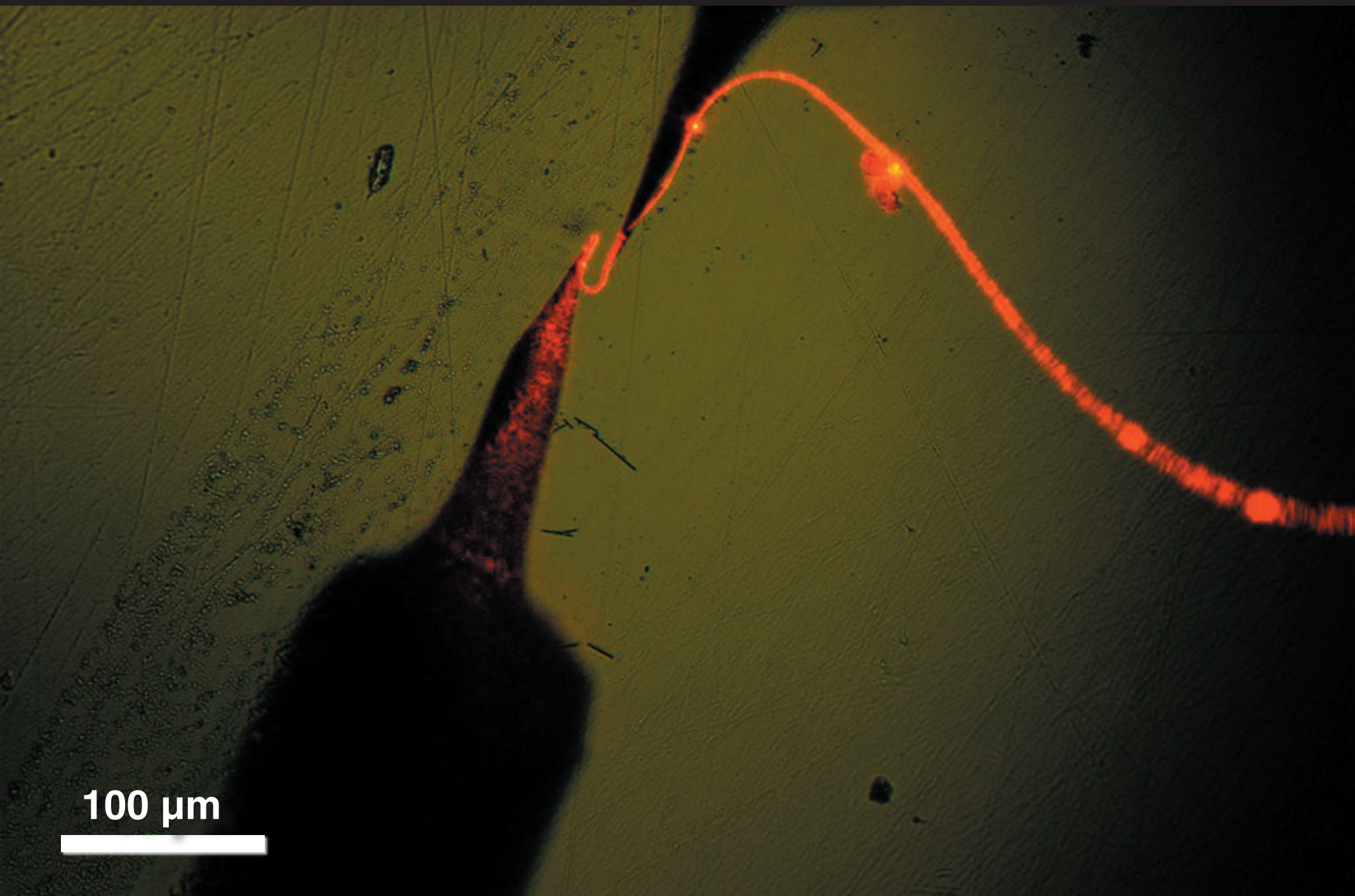


Optical properties



100 μm

Optical properties

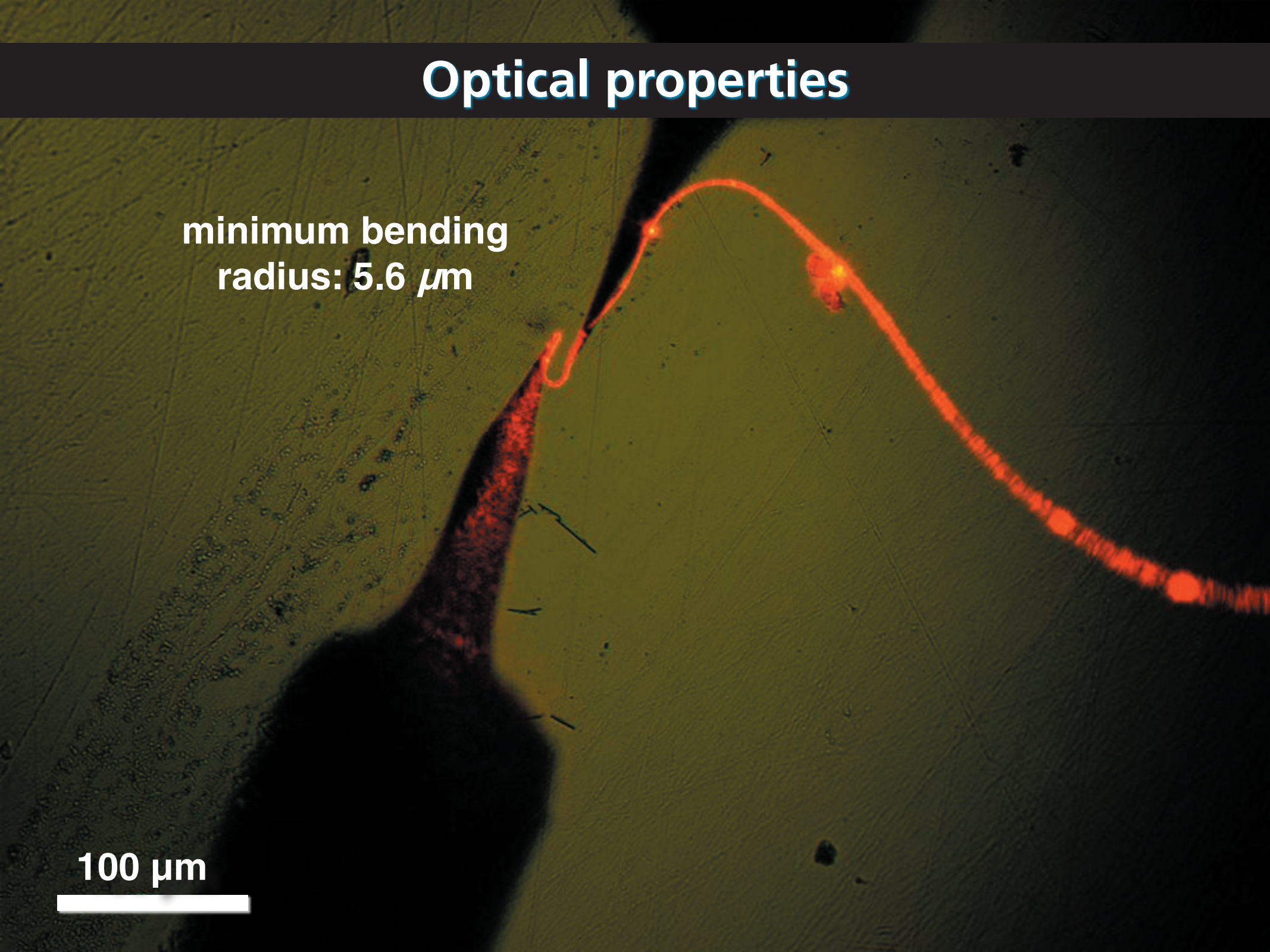


100 μm

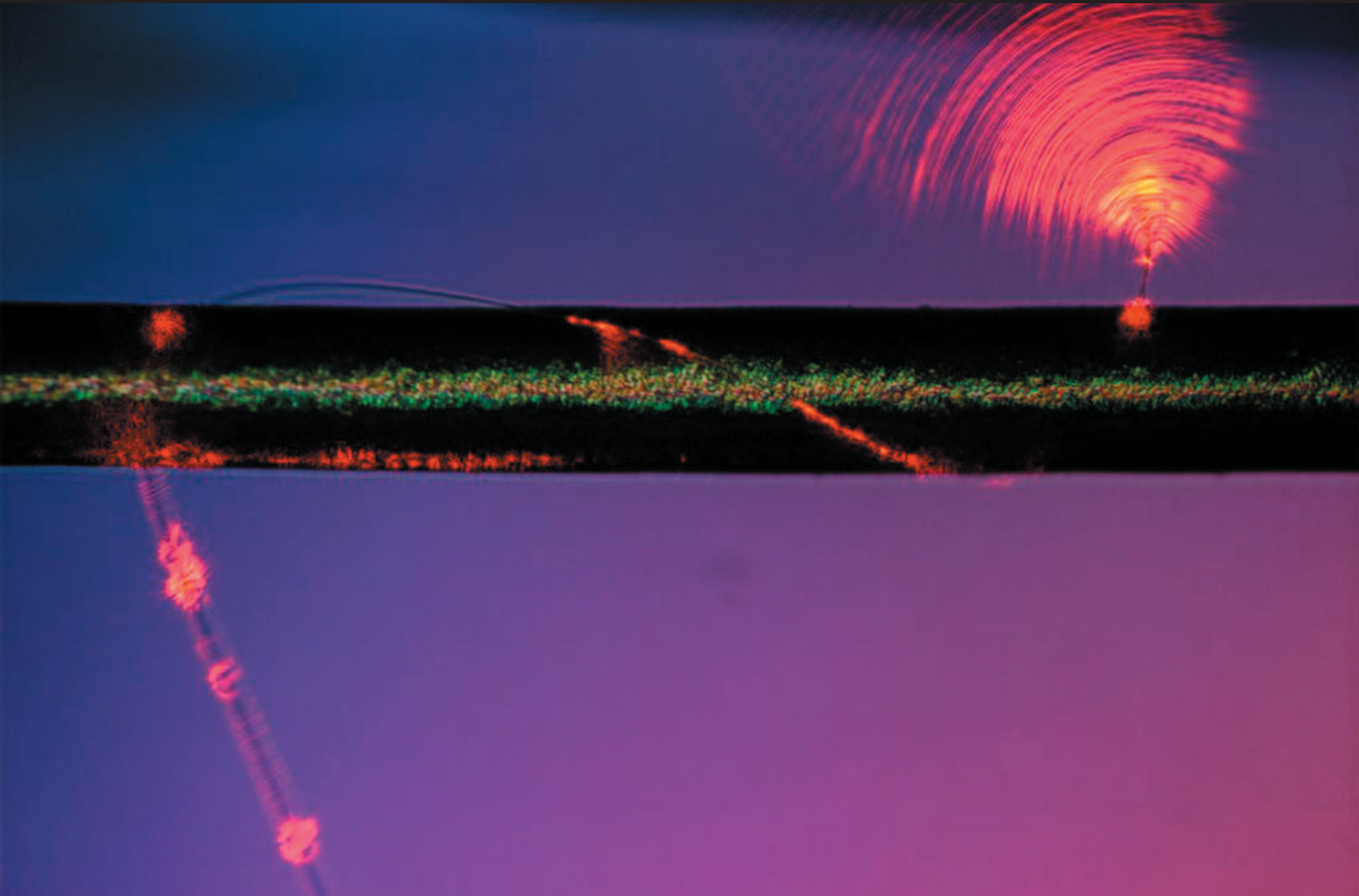
Optical properties

minimum bending
radius: $5.6 \mu\text{m}$

100 μm

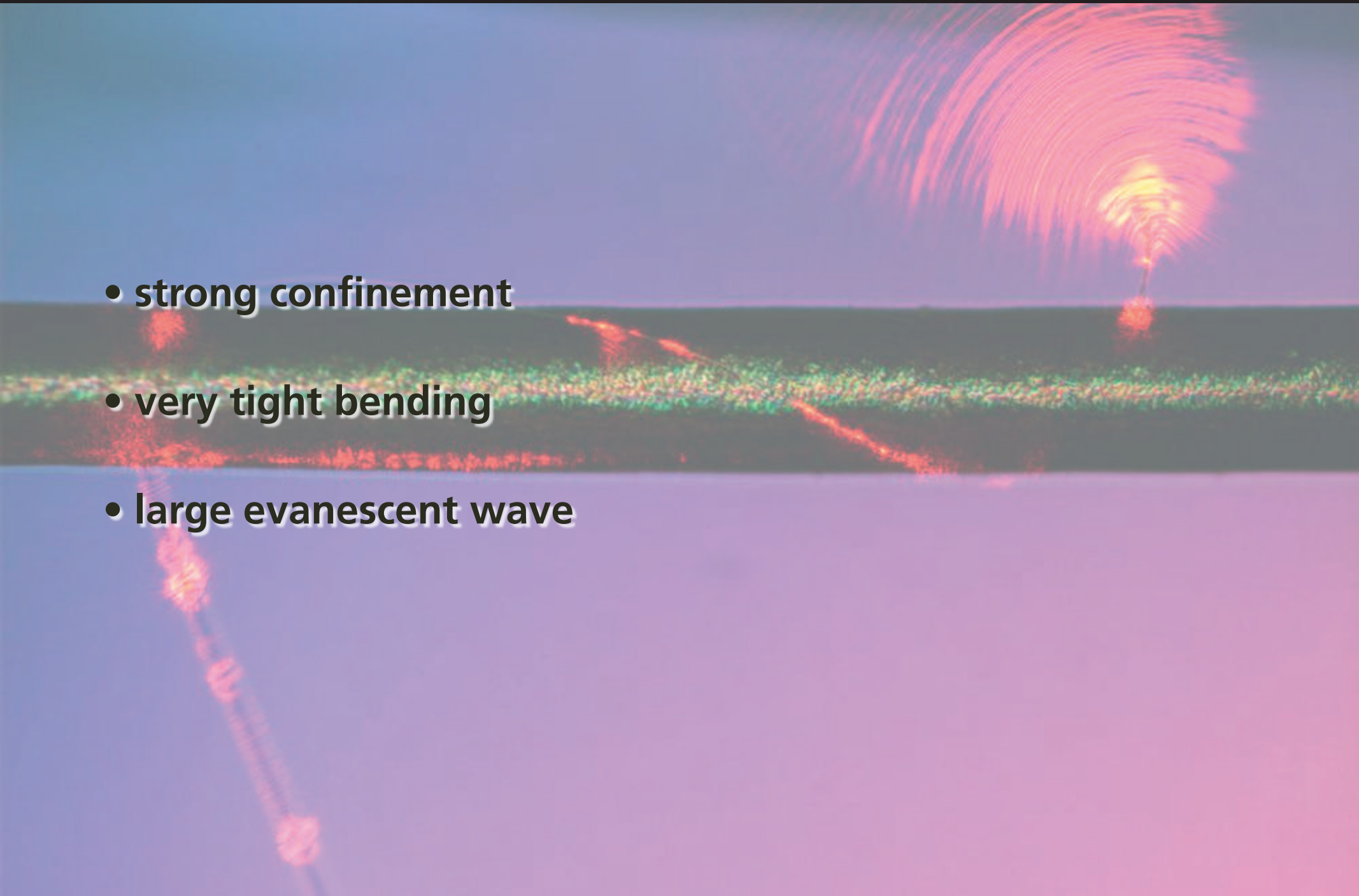
An optical micrograph showing a fiber optic cable. A red laser light path is visible, starting from a point on the left, curving upwards and then downwards to the right. The fiber is dark against a light greenish-yellow background. A scale bar at the bottom left indicates 100 micrometers. Text in the upper left corner states the minimum bending radius is 5.6 micrometers.

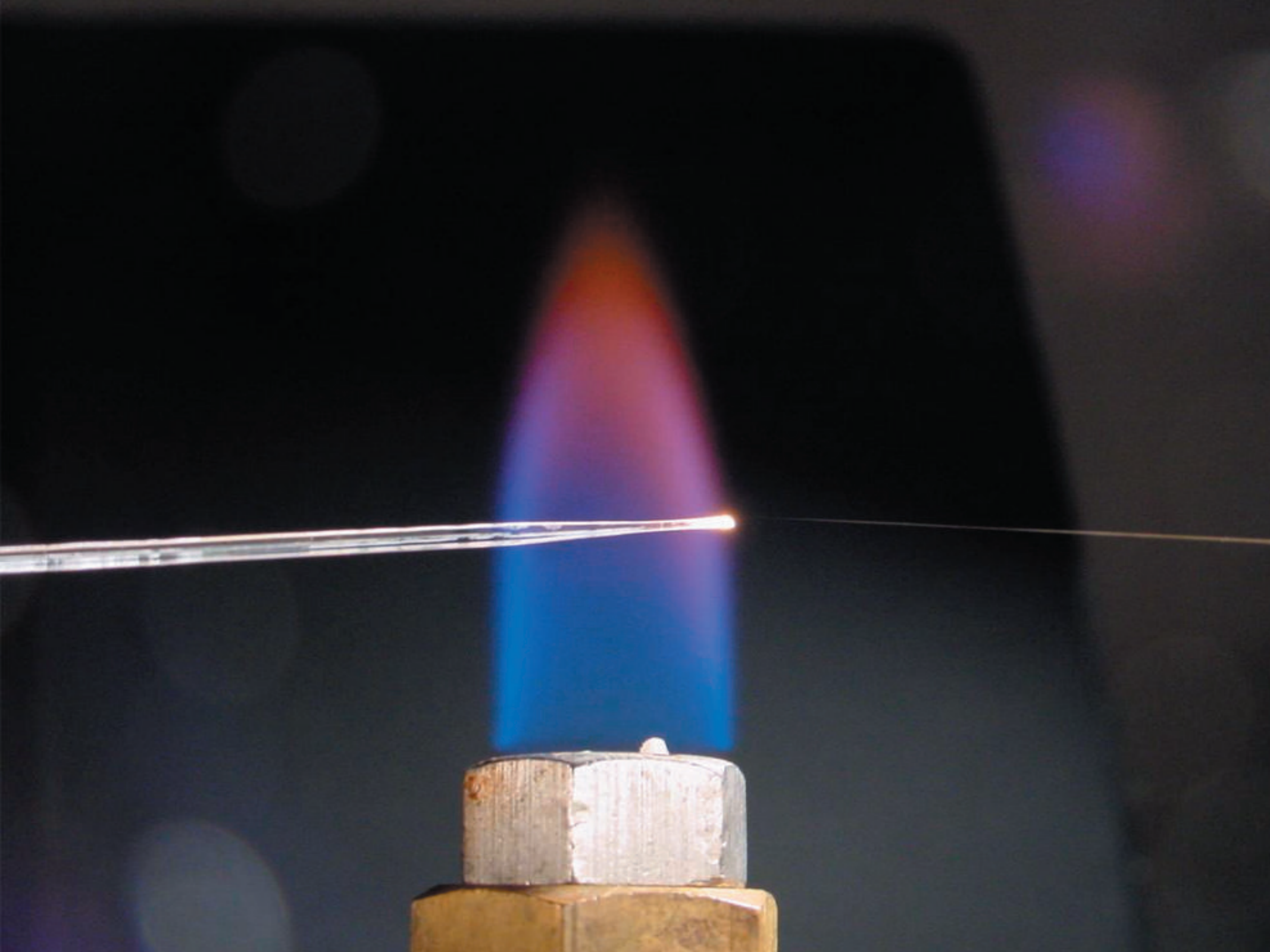
Summary



Summary

- strong confinement
- very tight bending
- large evanescent wave









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**Harvard Center for Imaging and Mesoscopic Structures
National Science Foundation
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