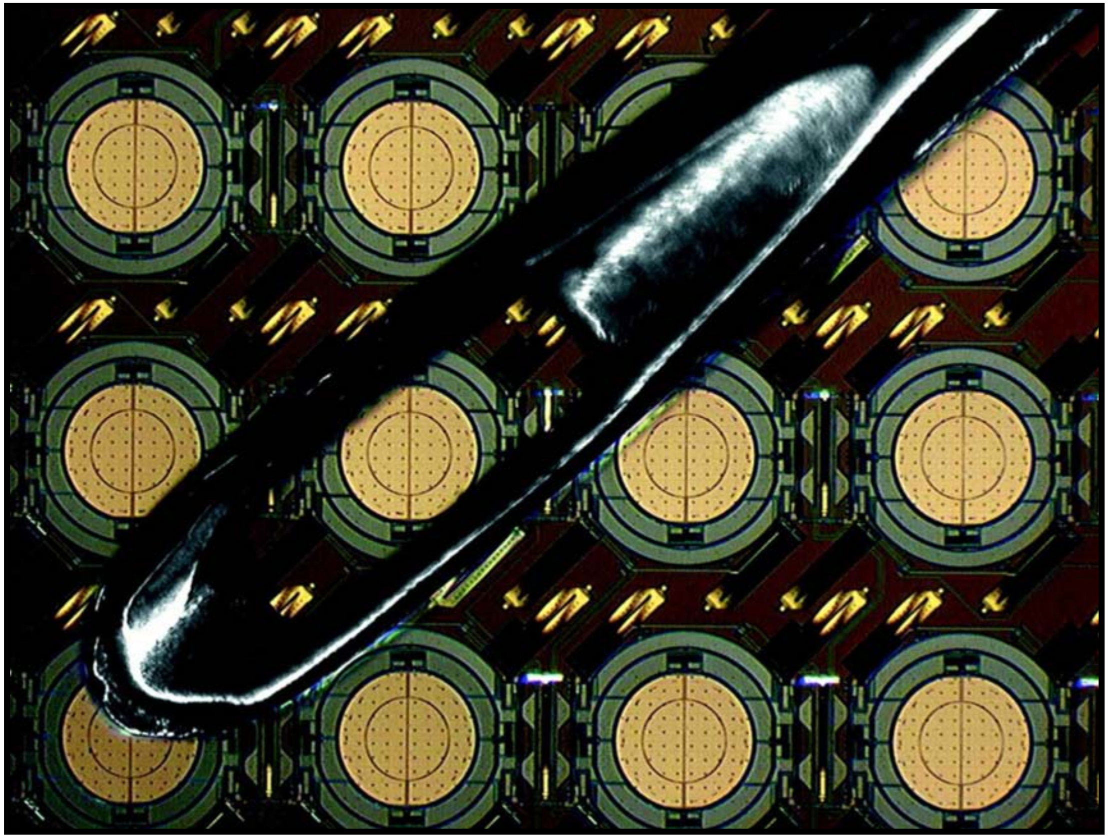
Nanomaterials

Lecture 18:
Nanoelectromechanical Systems

Nanoelectromechanical Systems



H. G. Craighead, *Science*, **290**, 1532 (2000).

Poly-Silicon Thin Film Processing

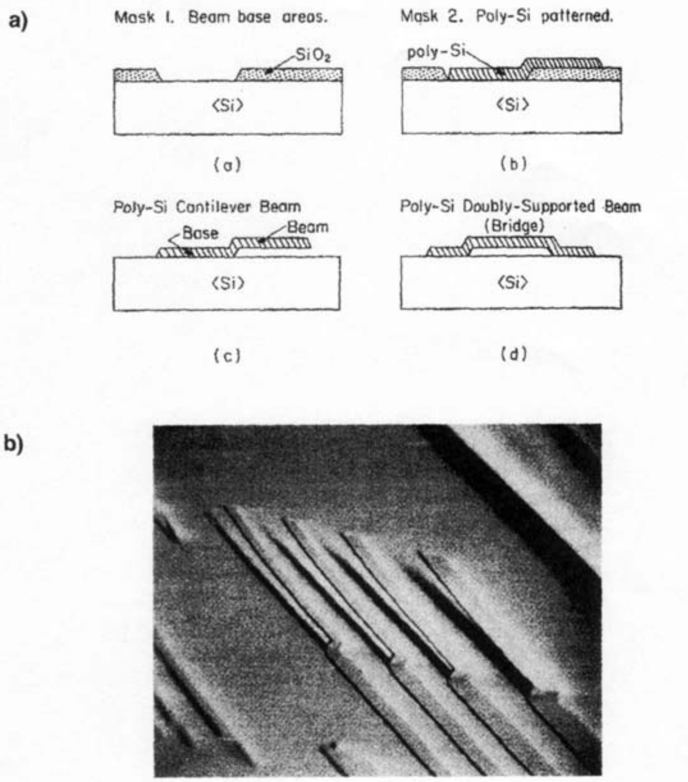


FIGURE 2. Surface micro-machined polycrystalline (a) Silicon process[7], and (b) Cantilever beams.

→ Problems with uniformity of thin films and built-in strain

Single Crystal Reactive Etching and Metallization (SCREAM)

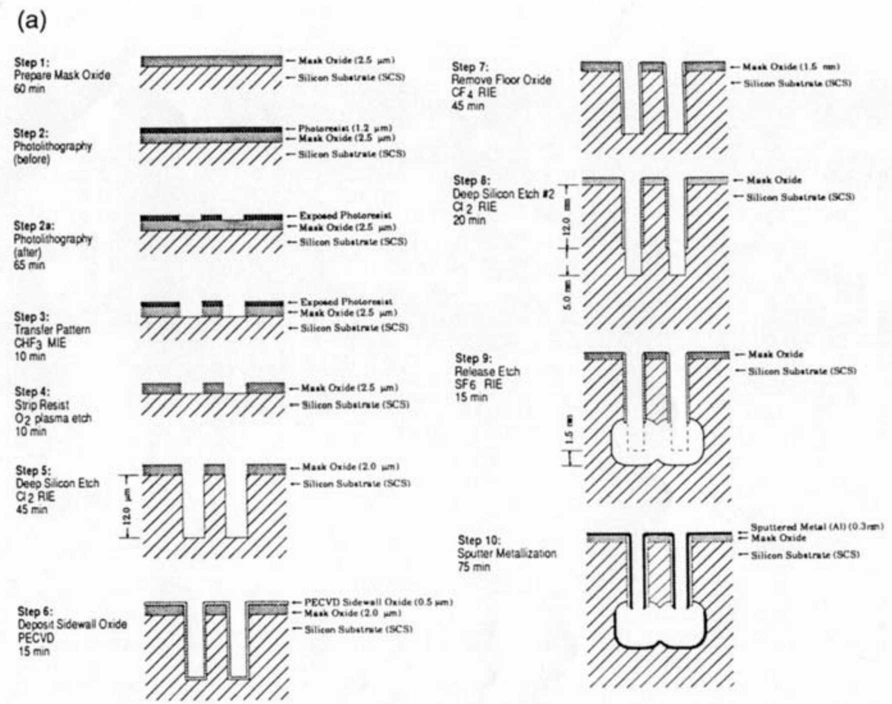
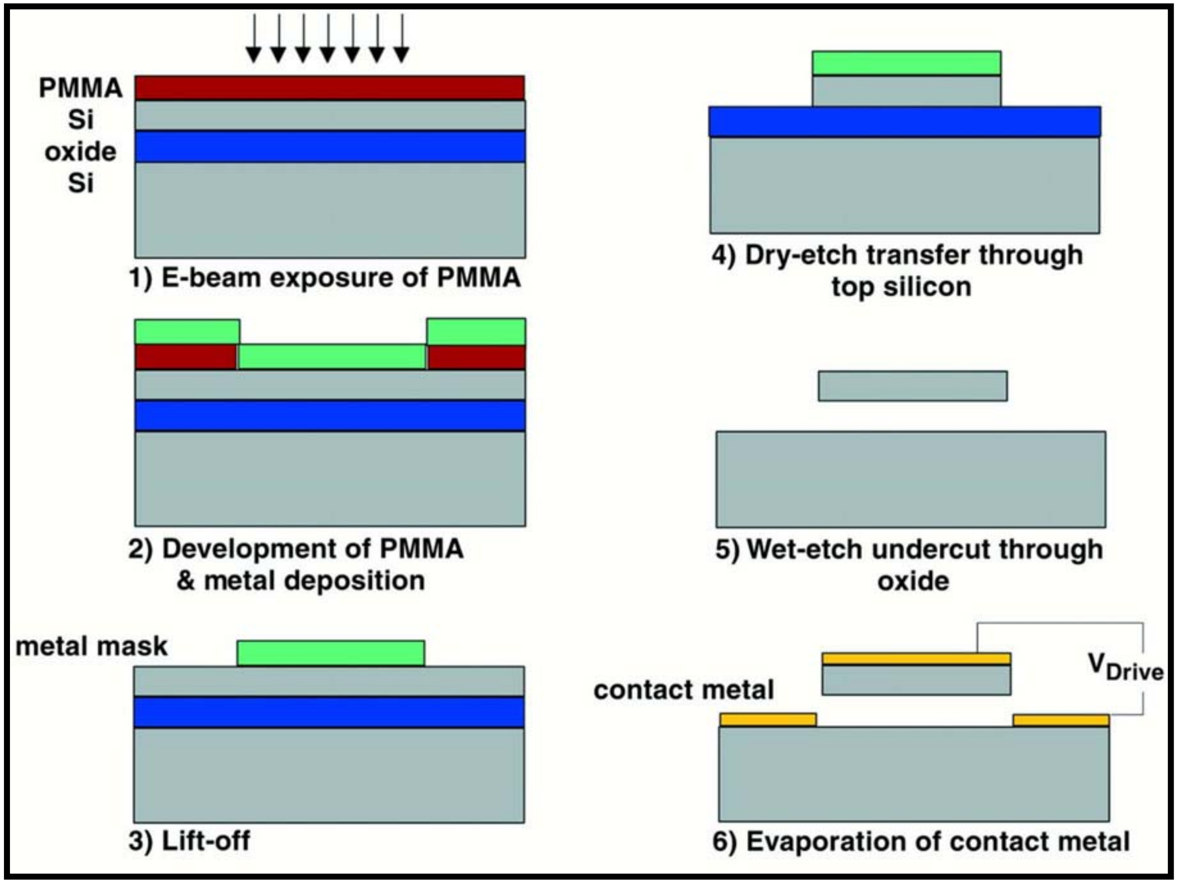


FIGURE 24. Low temperature version of SCREAM process. (a) Process sequence for low temperature version of SCREAM that uses isolated MESA structures for an anchor and bonding pads.

Suspended single crystal silicon → E ~ 130 GPa (comparable to steel)

MEMS Fabrication using Silicon-on-Insulator Substrates



H. G. Craighead, *Science*, **290**, 1532 (2000).

Capacitive Micro-Actuator

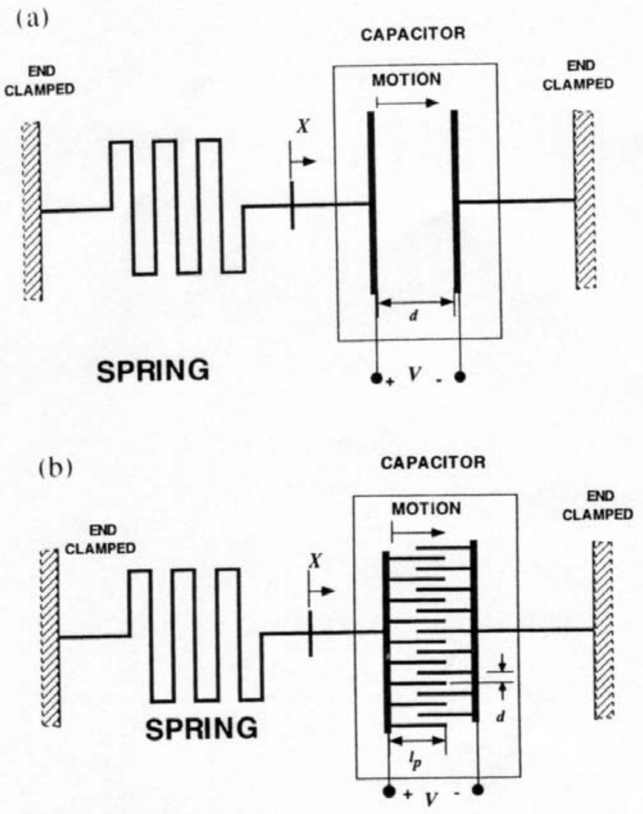


FIGURE 7. Capacitor micro-actuators (a) Parallel-plate micro-actuator with maximum displacement of *d*. (b) Interdigitated electrode or comb drive capacitor micro-actuator with maximum displacement proportional to l_p – not *d*.

Capacitive Micro-Actuator

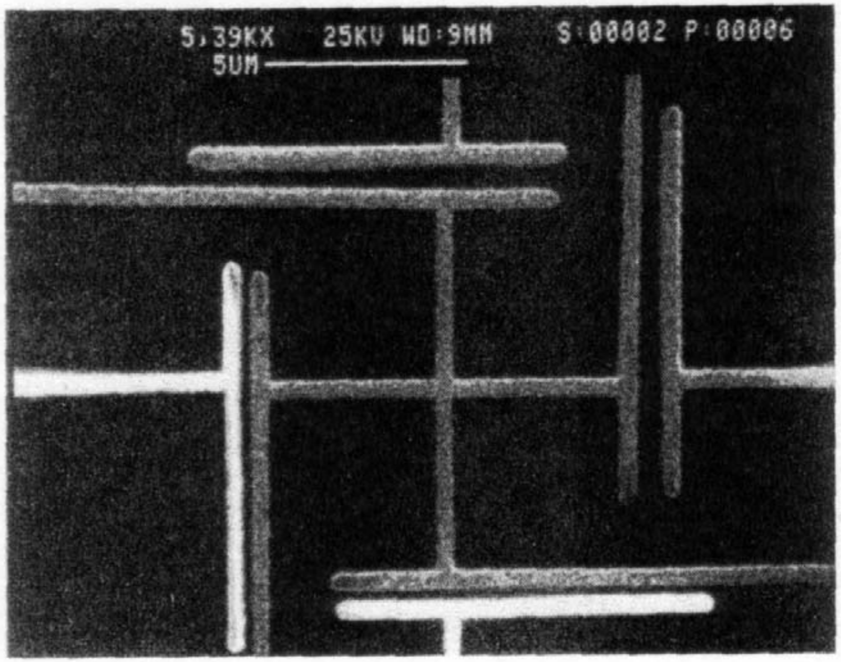


FIGURE 8. SEM micrograph of four parallel-plate capacitors suspended by springs. The cross in the center has been displaced downward and to the left by actuation of two sets of plates – white plates are negative. The single crystal silicon plates are 10 µm × 200 nm.

Capacitive Displacement Sensor

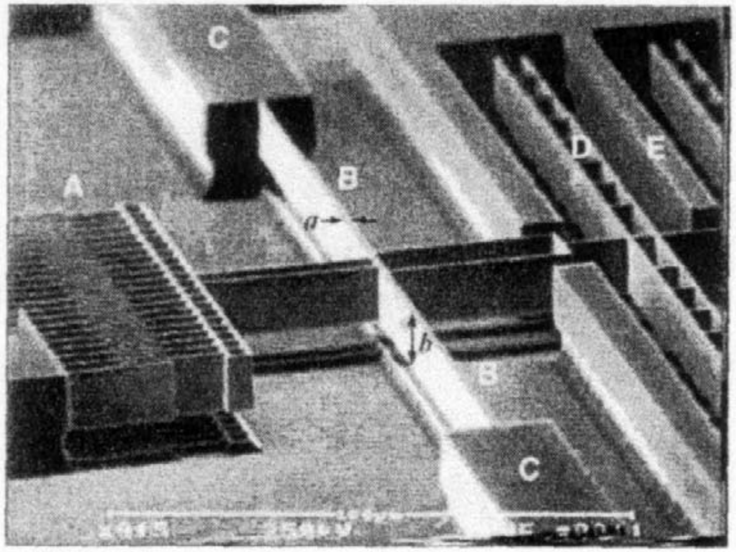


FIGURE 9. A high aspect-ratio (*b*/*a*) single crystal silicon device made using SCREAM processes[63]. [A]-Interdigitated electrode micro-actuator that moves the structure to the left when a voltage is applied to the two sets of electrodes. [B]-Suspended spring with supports-[C]; [D]-Moving suspended plate of a parallel-plate capacitor attached to the spring and a fixed plate [E]. The parallel-plate capacitor is used to sense displacement.

Torsional Micro-Actuator

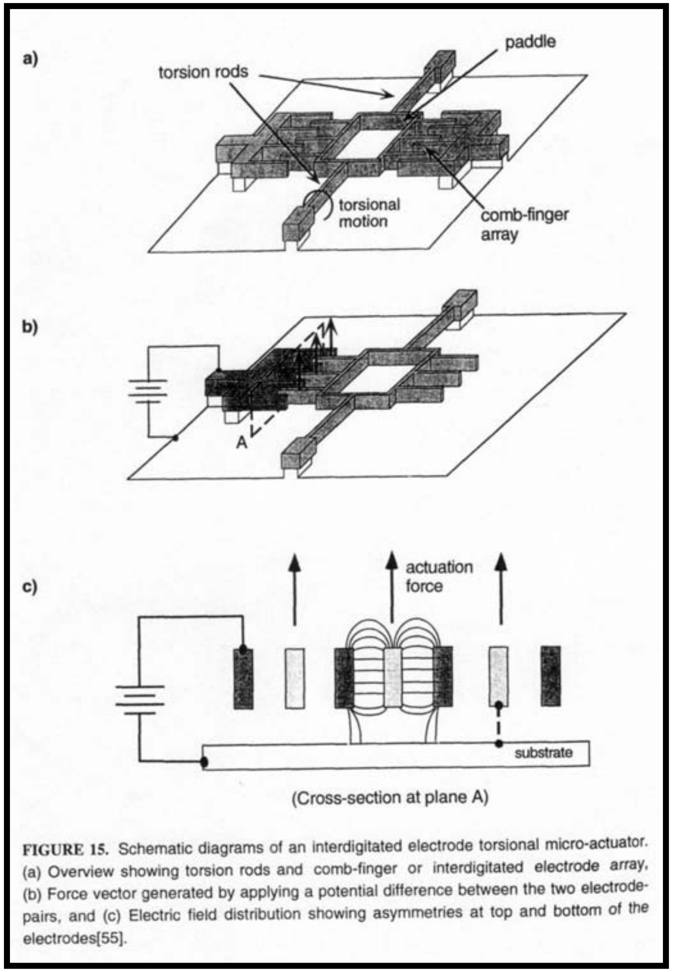


FIGURE 15. Schematic diagrams of an interdigitated electrode torsional micro-actuator. (a) Overview showing torsion rods and comb-finger or interdigitated electrode array, (b) Force vector generated by applying a potential difference between the two electrode-pairs, and (c) Electric field distribution showing asymmetries at top and bottom of the electrodes[55].

Asymmetry in electric field lines actuate vertical motion

Torsional Micro-Actuator

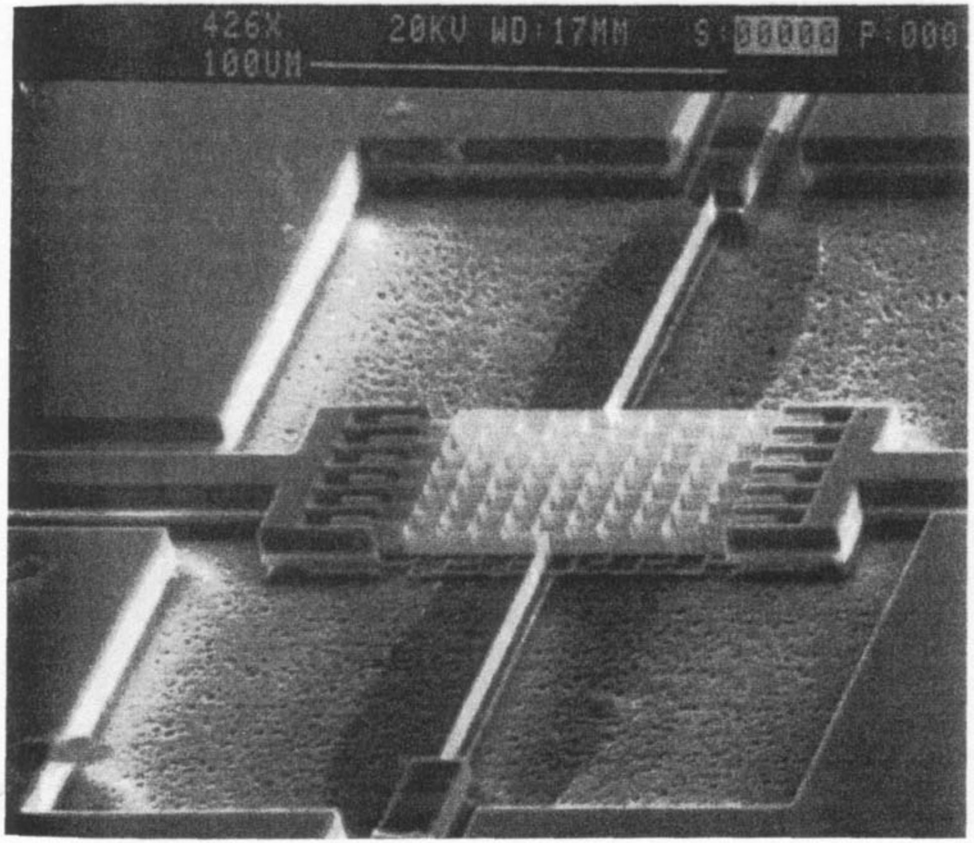
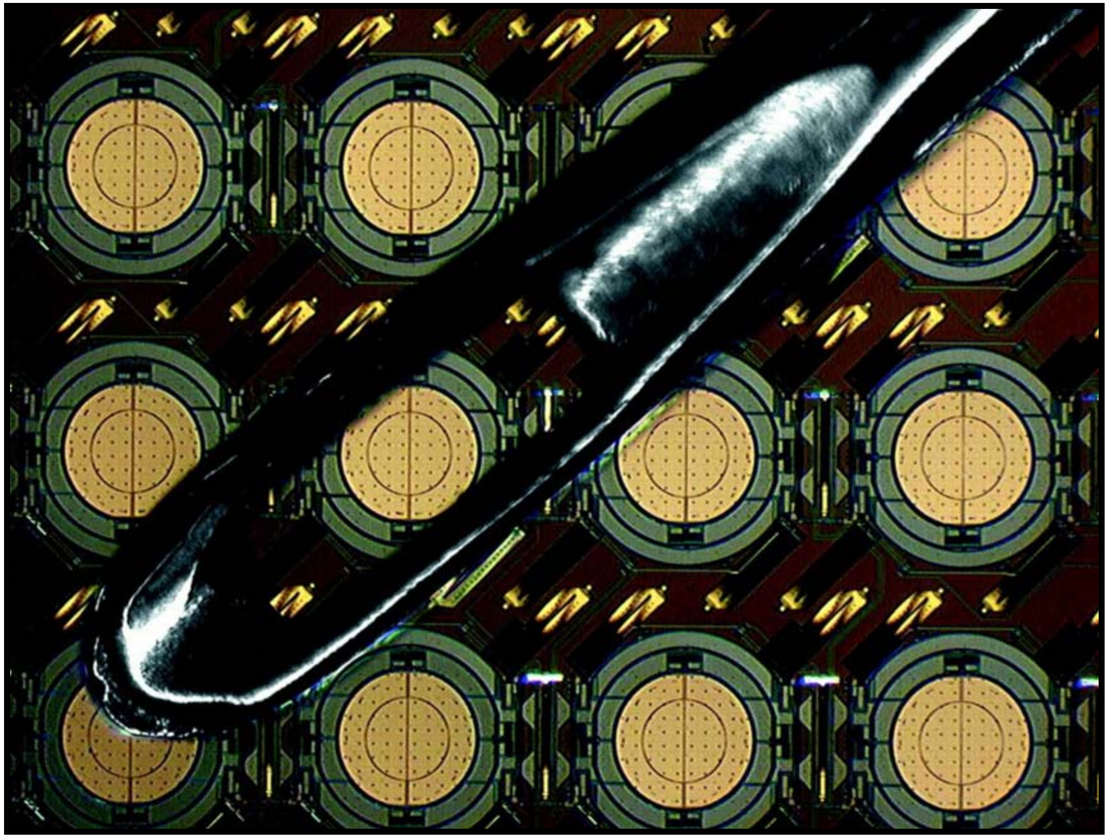


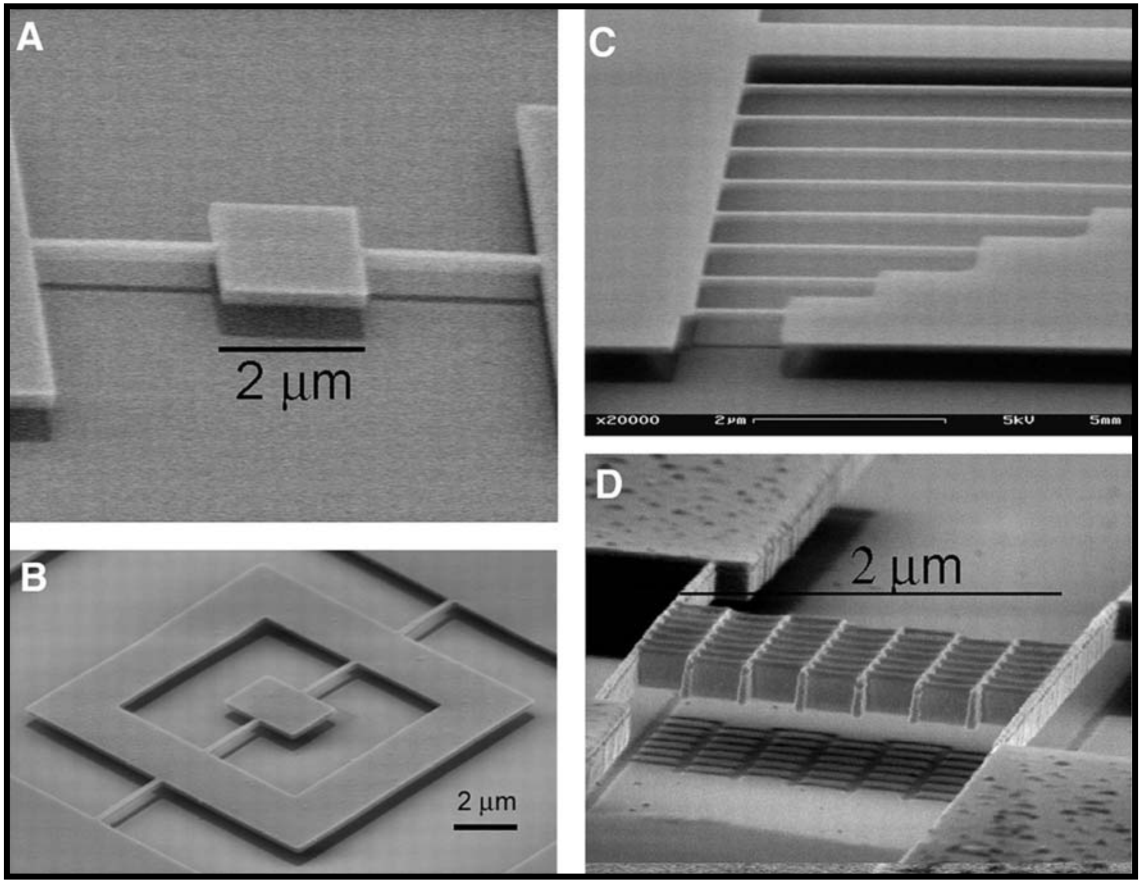
FIGURE 14. An SEM micrograph of a single crystal silicon, torsional micro-actuator with interdigitated electrode drives[55].

Lucent Technologies Mirror Array



H. G. Craighead, *Science*, **290**, 1532 (2000).

Silicon Micromirrors and Nanowires



H. G. Craighead, *Science*, **290**, 1532 (2000).

Resonance Frequency of NEMS Structures

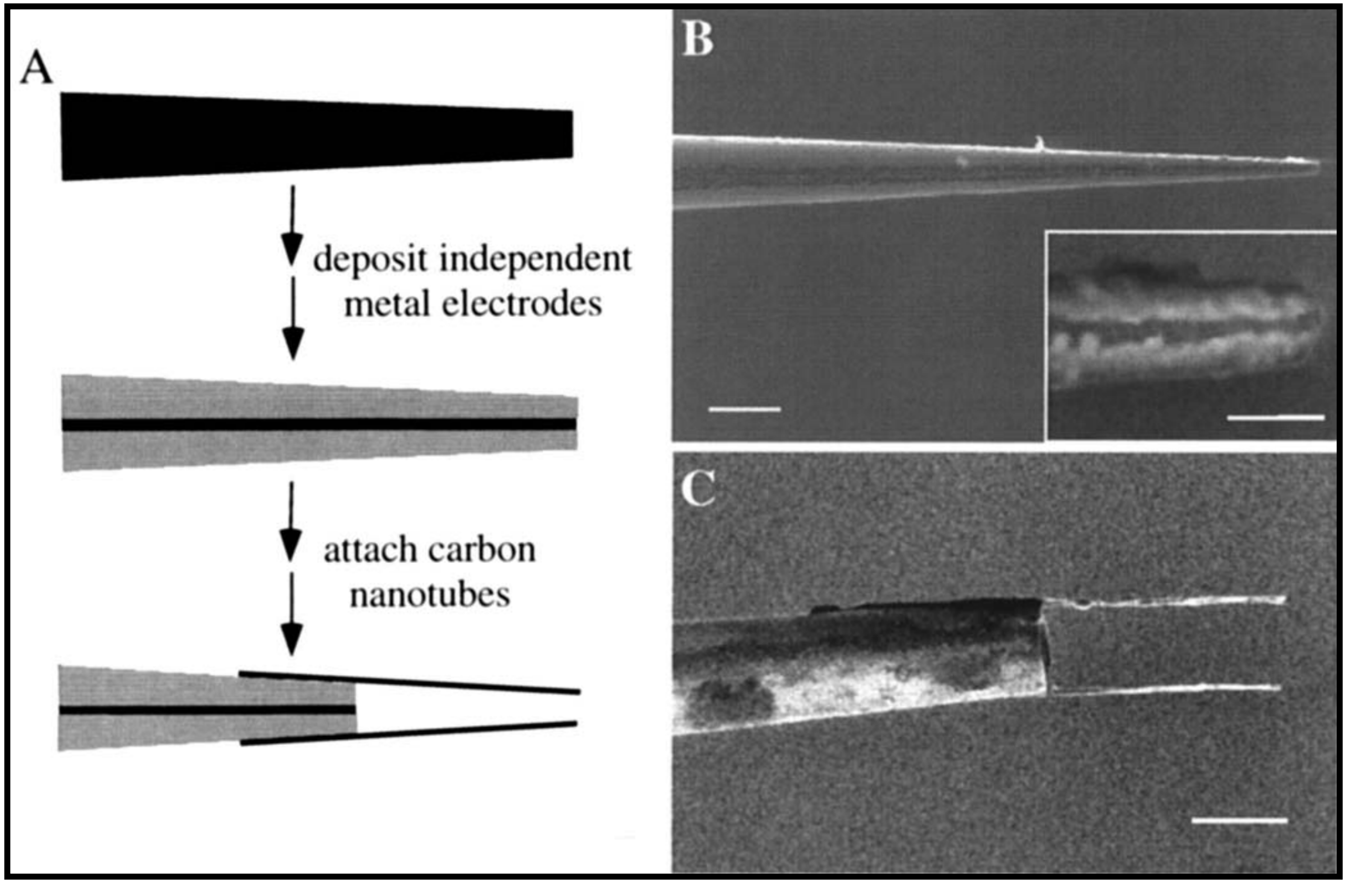
Resonant frequency of a doubly clamped beam:

$$f_0 = \frac{(4.730)^2}{2\pi} \frac{1}{l^2} \sqrt{\frac{EI}{\rho A}}$$

Note: 2 µm long, 50 nm wide wires have $f_0 \sim 400$ MHz

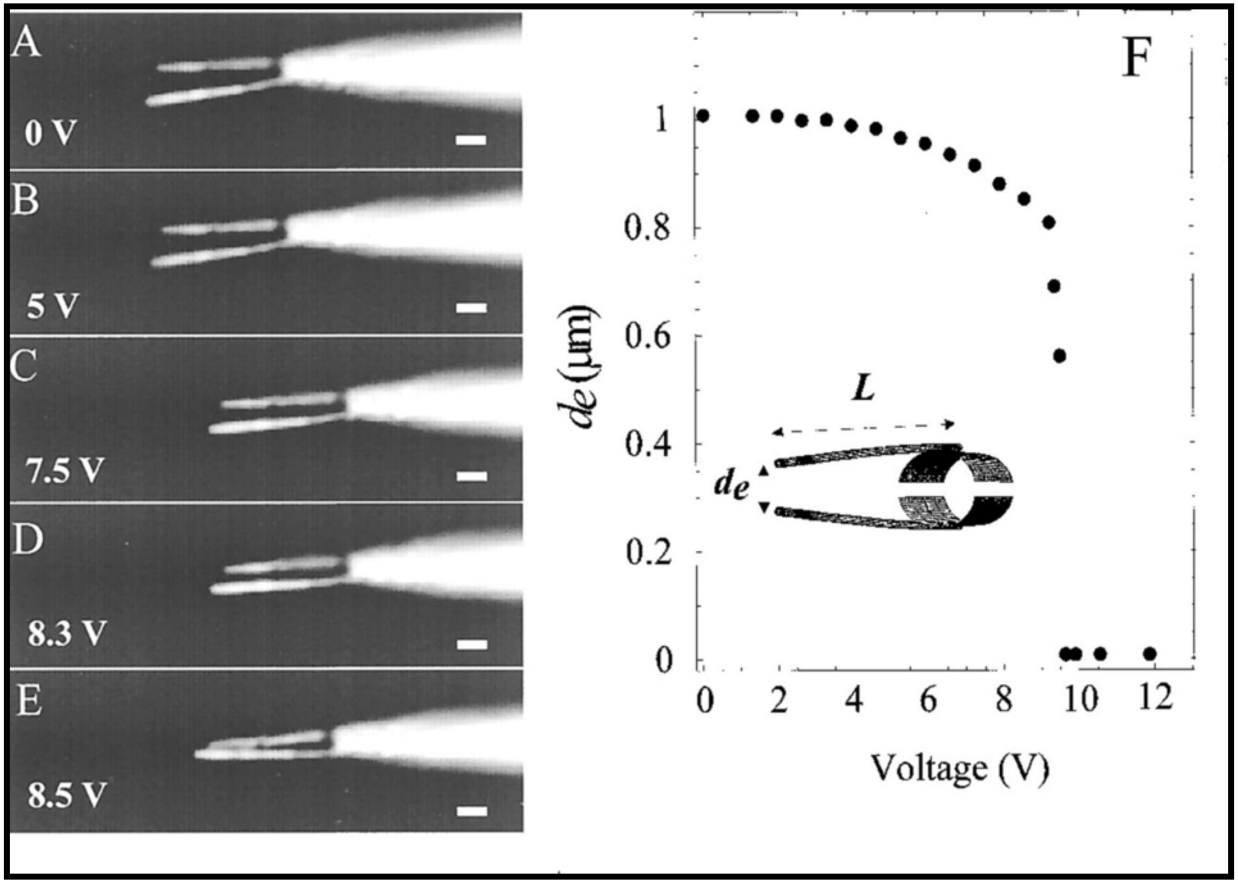
→ Resonance frequency inversely scales with size

Carbon Nanotube Tweezers



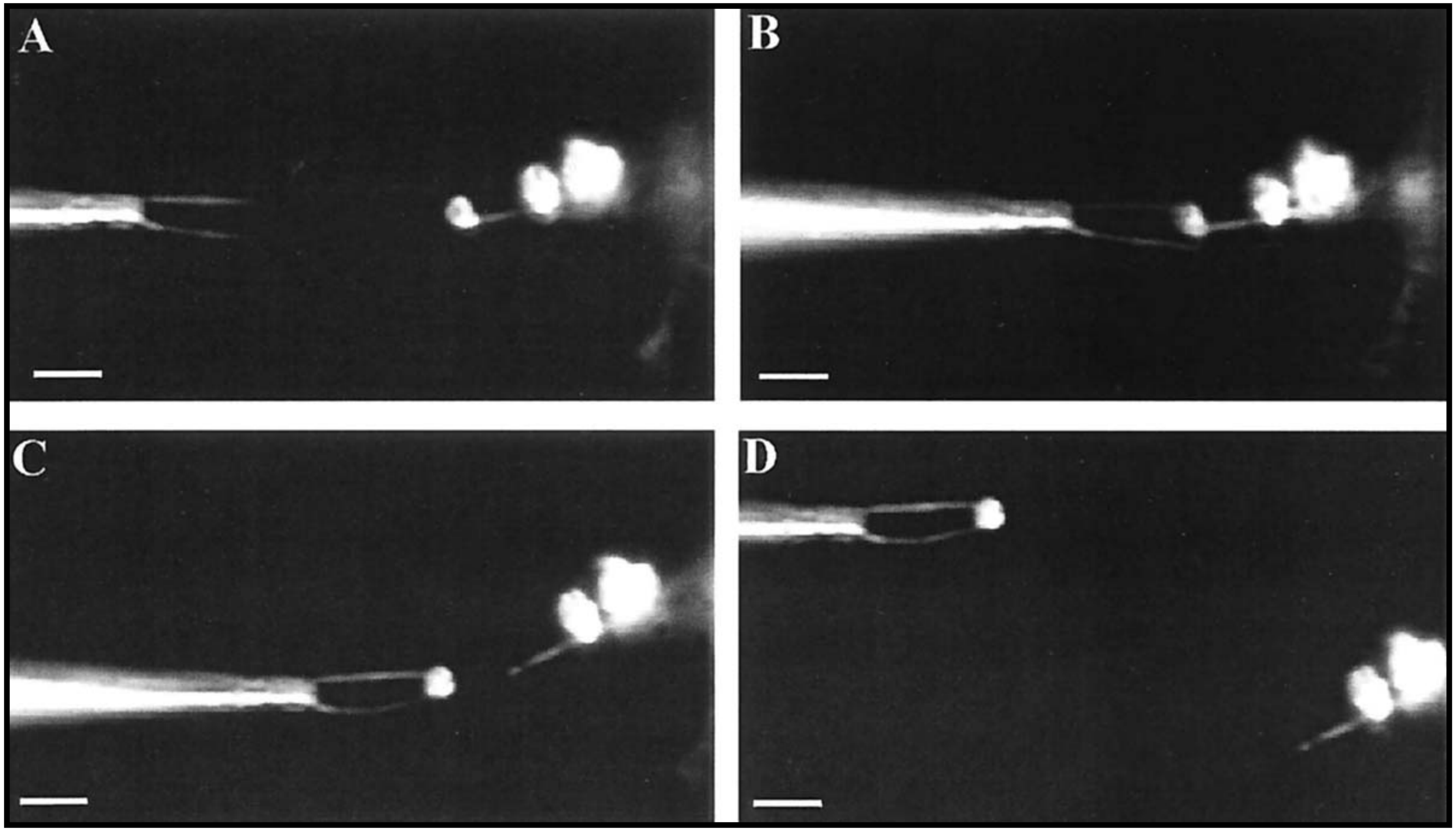
P. Kim and C. M. Lieber, *Science*, **286**, 2148 (1999).

Carbon Nanotube Tweezers



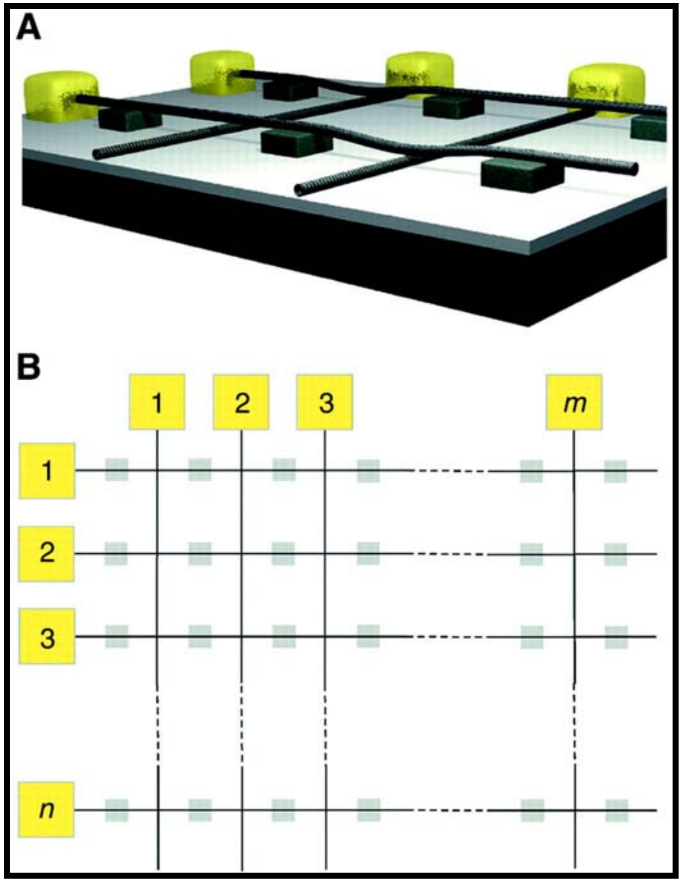
P. Kim and C. M. Lieber, *Science*, **286**, 2148 (1999).

Carbon Nanotube Tweezers



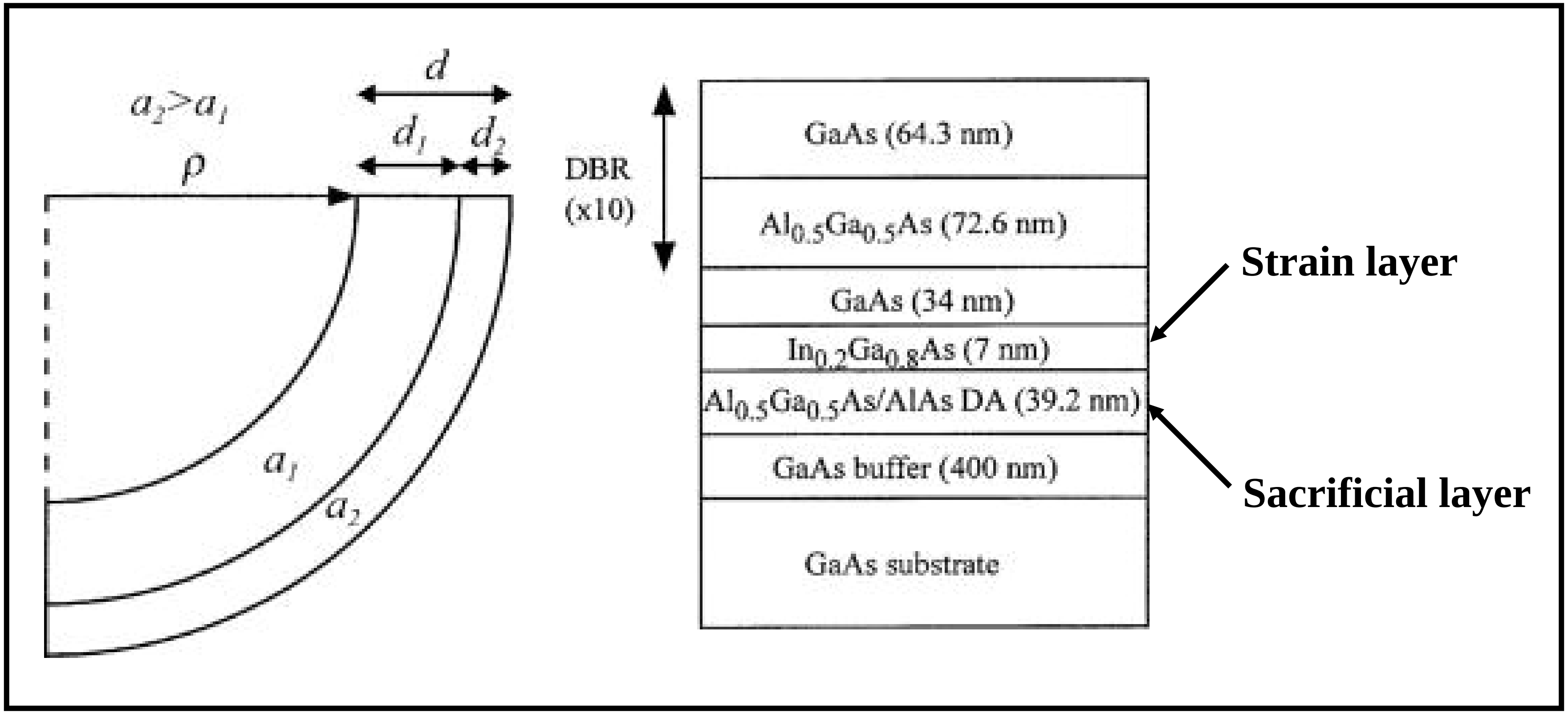
P. Kim and C. M. Lieber, *Science*, **286**, 2148 (1999).

Nonvolatile Carbon Nanotube Memory



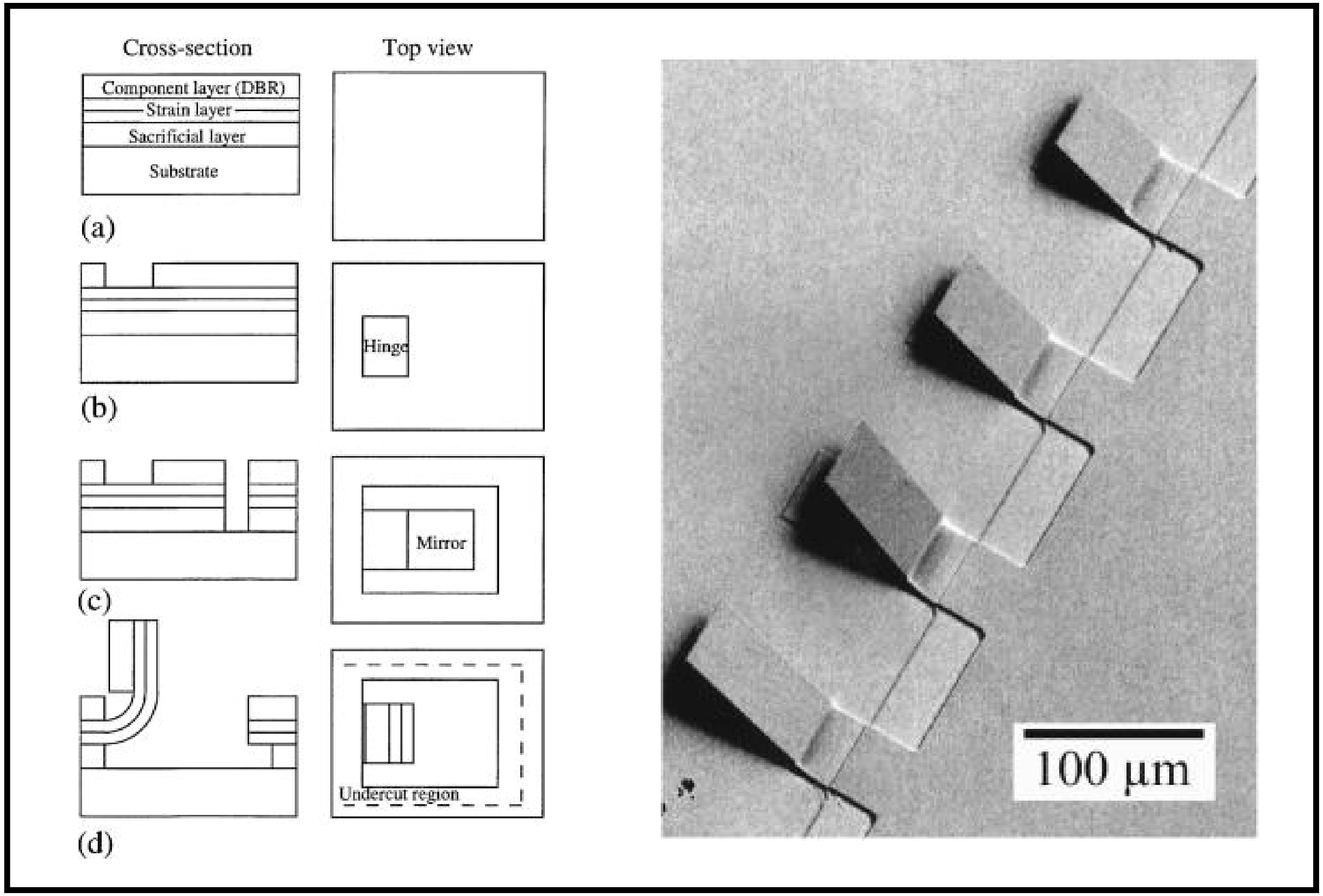
T. Rueckes, *et al.*, *Science*, **289**, 94 (2000).

Strain-driven Positioning of MEMS Structures



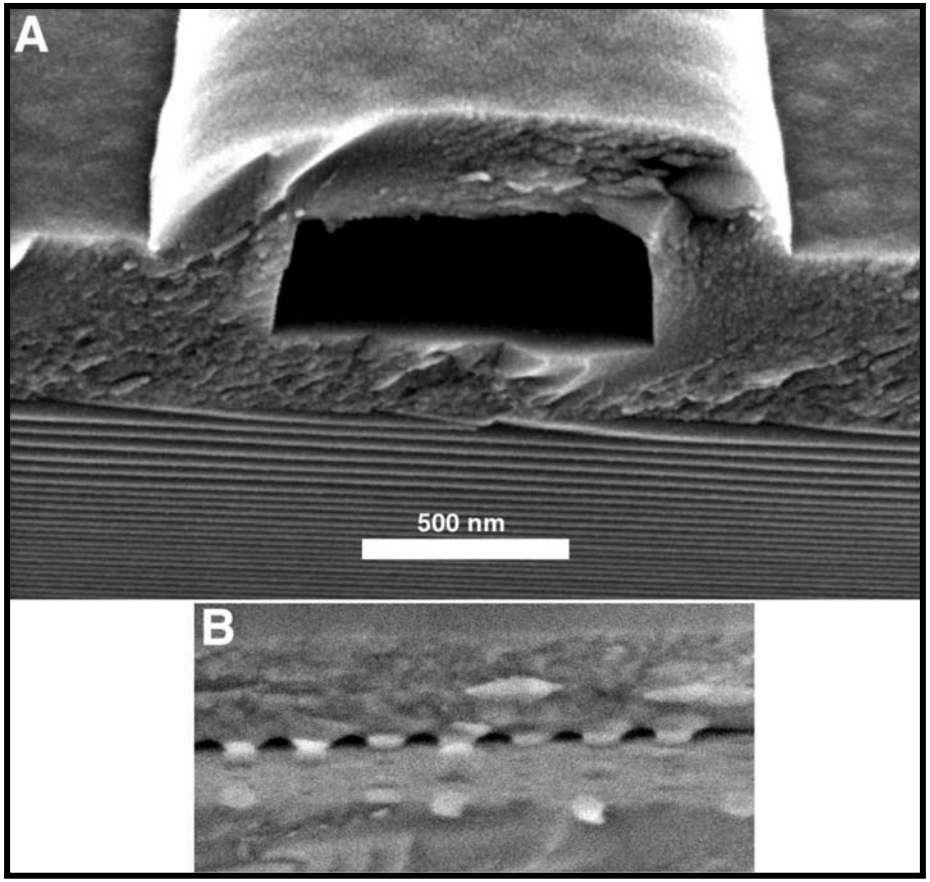
P. O. Vacaro, *et al.*, *Appl. Phys. Lett.*, **78**, 2852 (2001).

Strain-driven Positioning of MEMS Structures



P. O. Vacaro, *et al*., *Appl. Phys. Lett.*, **78**, 2852 (2001).

Microfluidic Channels



H. G. Craighead, *Science*, **290**, 1532 (2000).

Separation of DNA using Entropic Trapping

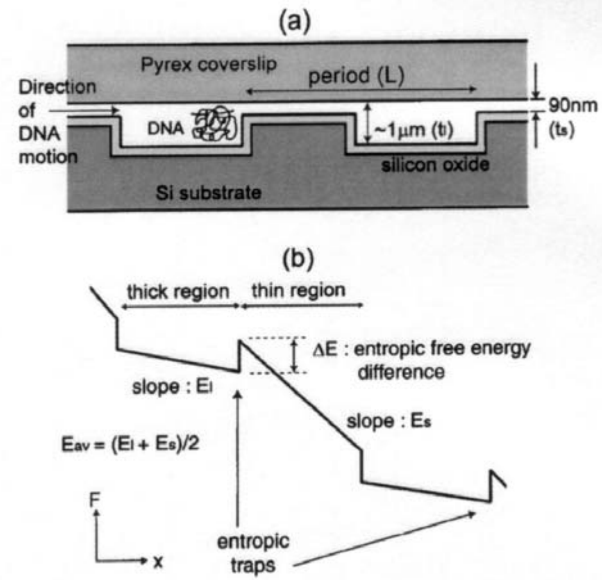
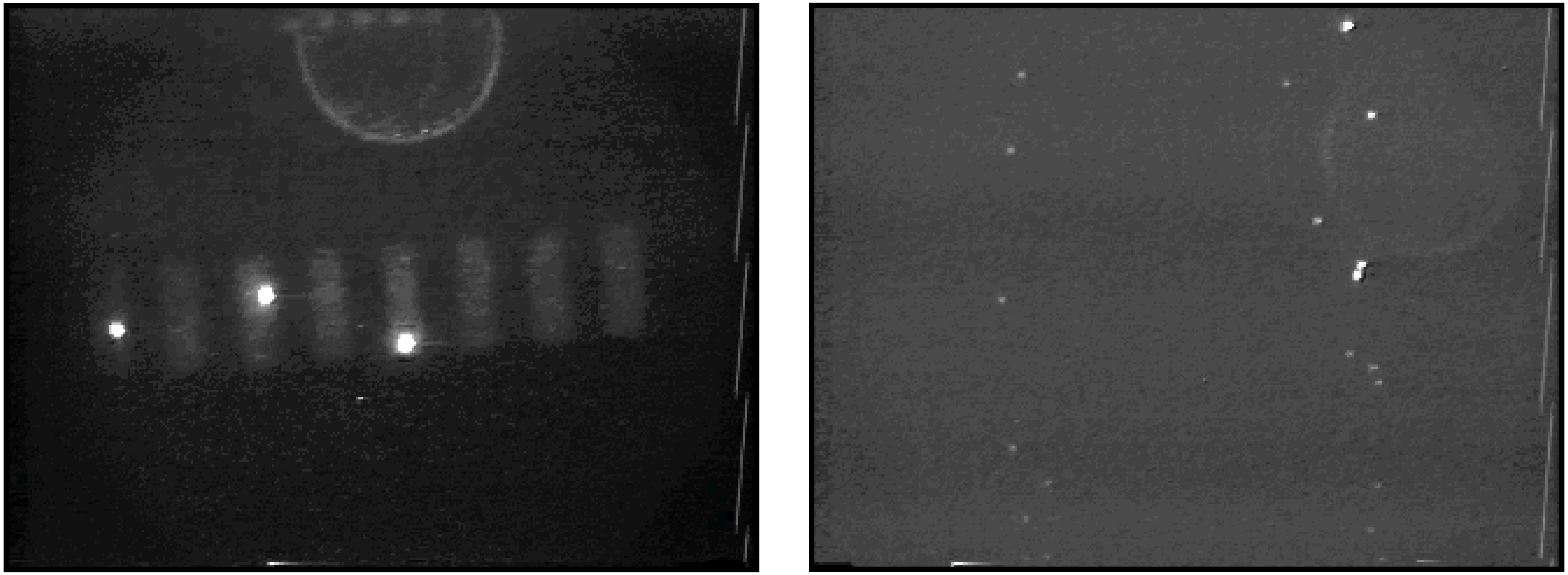


FIG. 1. (a) Schematic diagram of the device. (b) Free energy landscape for DNA in the channel. ΔE is the entropic free energy difference between a DNA molecule in a thick region and a thin region. E_s and E_l are the electric field at thin and thick regions, respectively. E_{av} is the average electric field over the channel.

J. Han, *et al.*, *Phys. Rev. Lett.*, **83**, 1688 (1999).

Separation of DNA using Entropic Trapping



J. Han and H. G. Craighead, *Science*, **288**, 1026 (2000).

Separation of DNA using Entropic Trapping

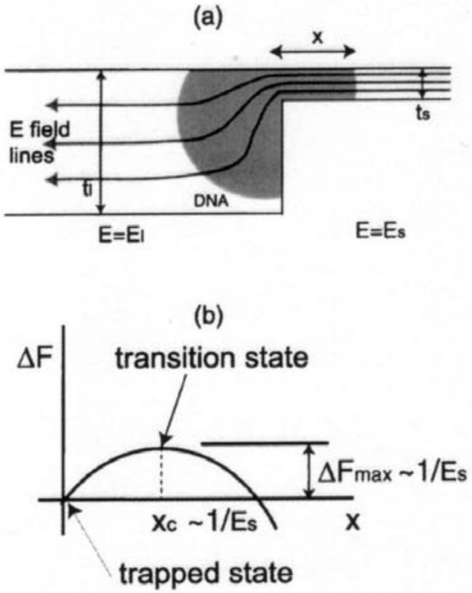
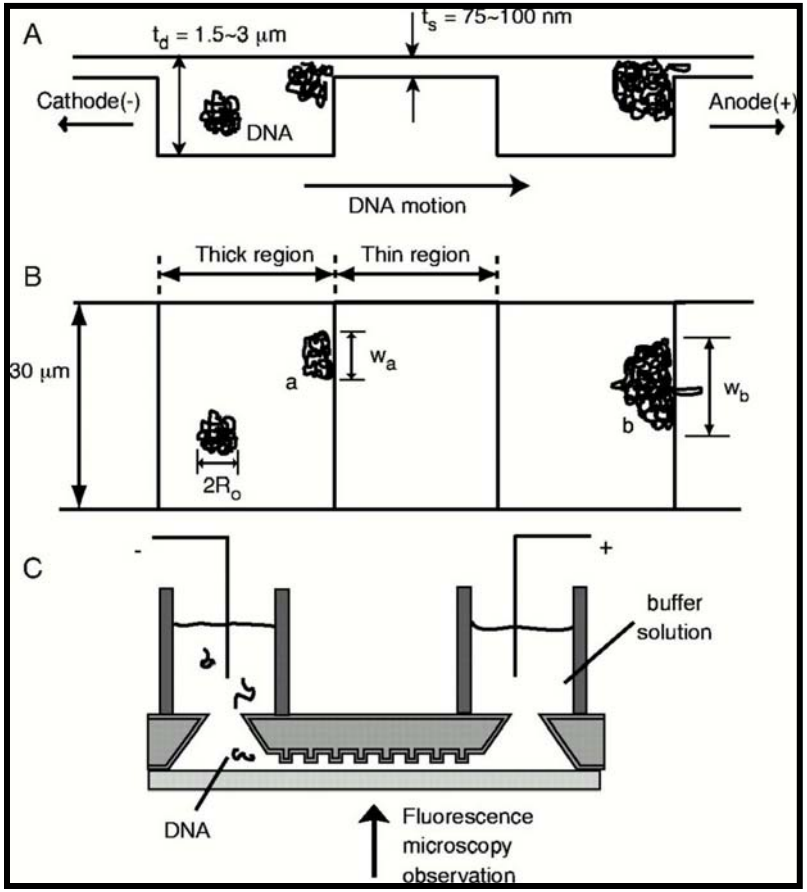


FIG. 4. (a) Escape of a DNA molecule from the trap. x is the length of DNA section in the thin region. (b) Plot of ΔF vs x. The transition state is when $x = x_c$.

J. Han, *et al.*, *Phys. Rev. Lett.*, **83**, 1688 (1999).

Separation of DNA using Entropic Trapping



J. Han and H. G. Craighead, *Science*, **288**, 1026 (2000).