Наномеханика

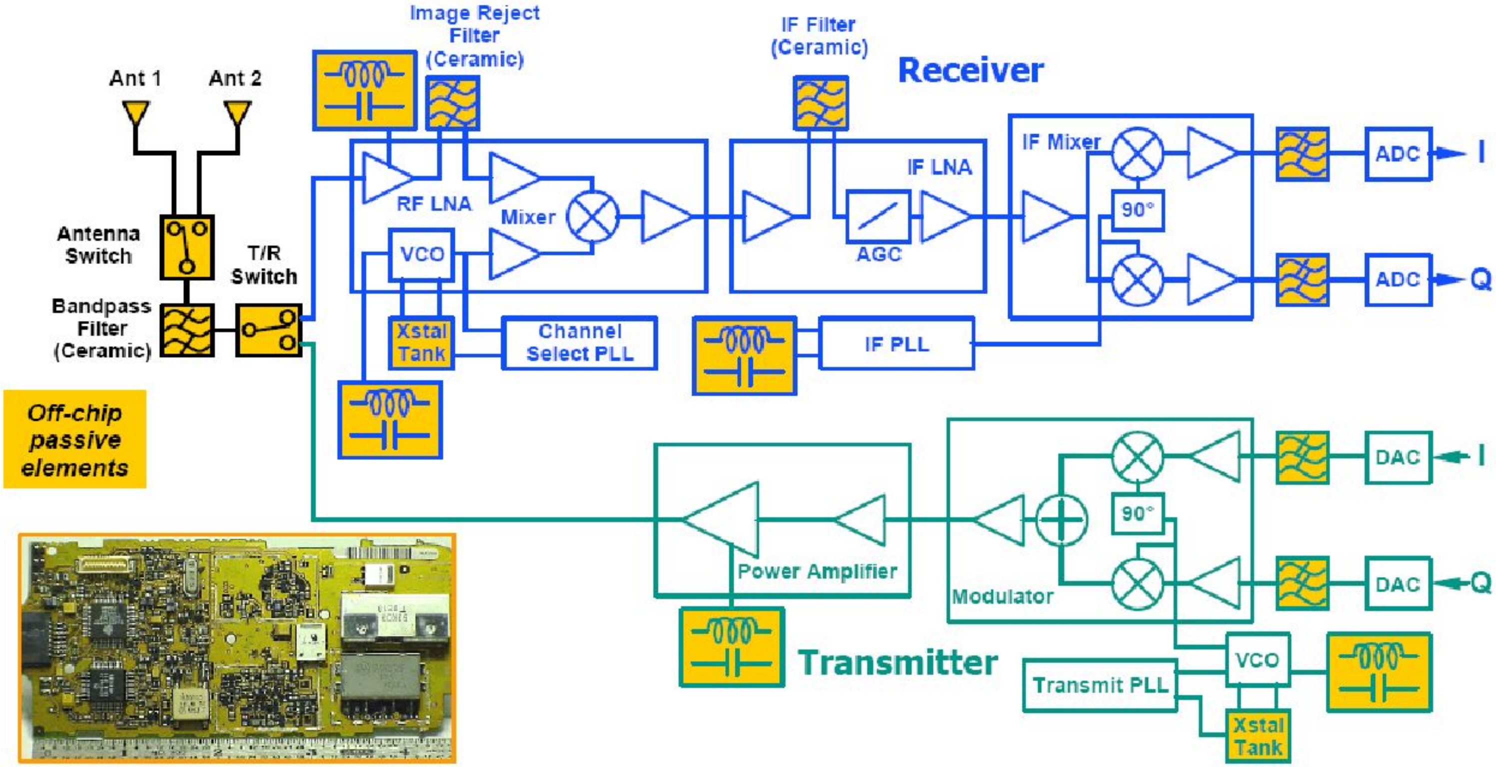
Nanomechanics of materials and systems

Лекции 15

МЭМС и НЭМС:
электронные системы, жидкостные вентили, насосы и биомедицинские системы

MEMS and NEMS electronic systems fluid valves, pumps and biomedical systems

Замещение пассивных электронных элементов
Replacement of passive electronic components



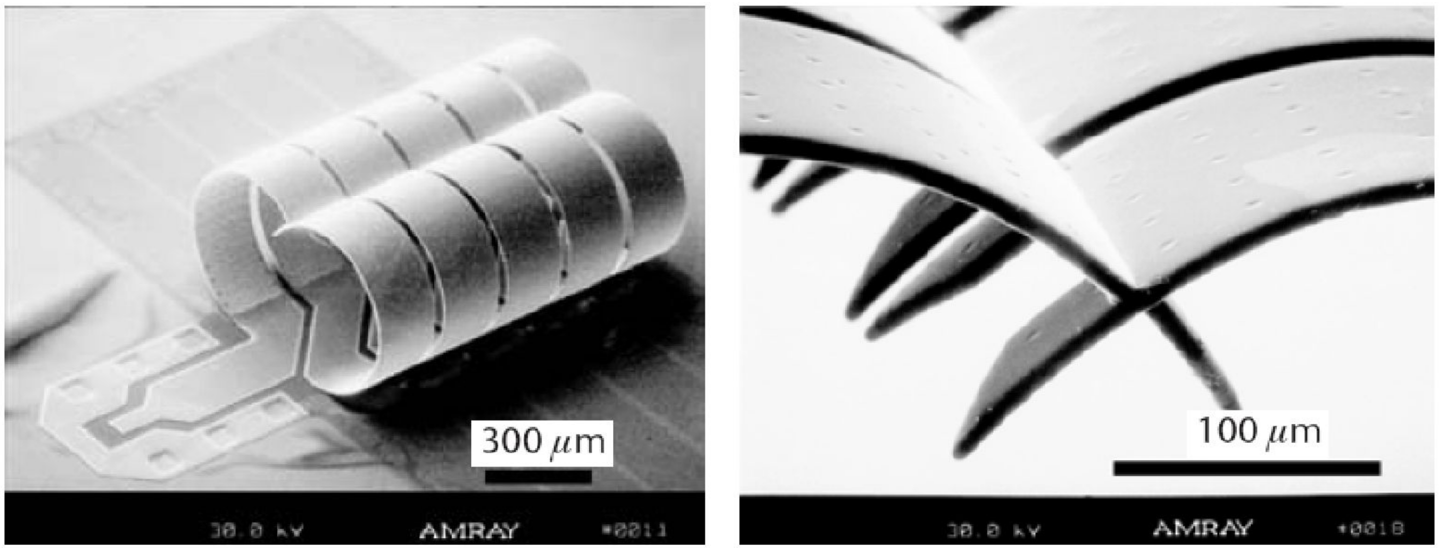
Current Cell Phone Board

Off-chip C & L = 80% of area

Current research:

✓ **Replace all off-chip passive elements with MEMS resonators & filters ⇒ chip-scale integration & improved performance**

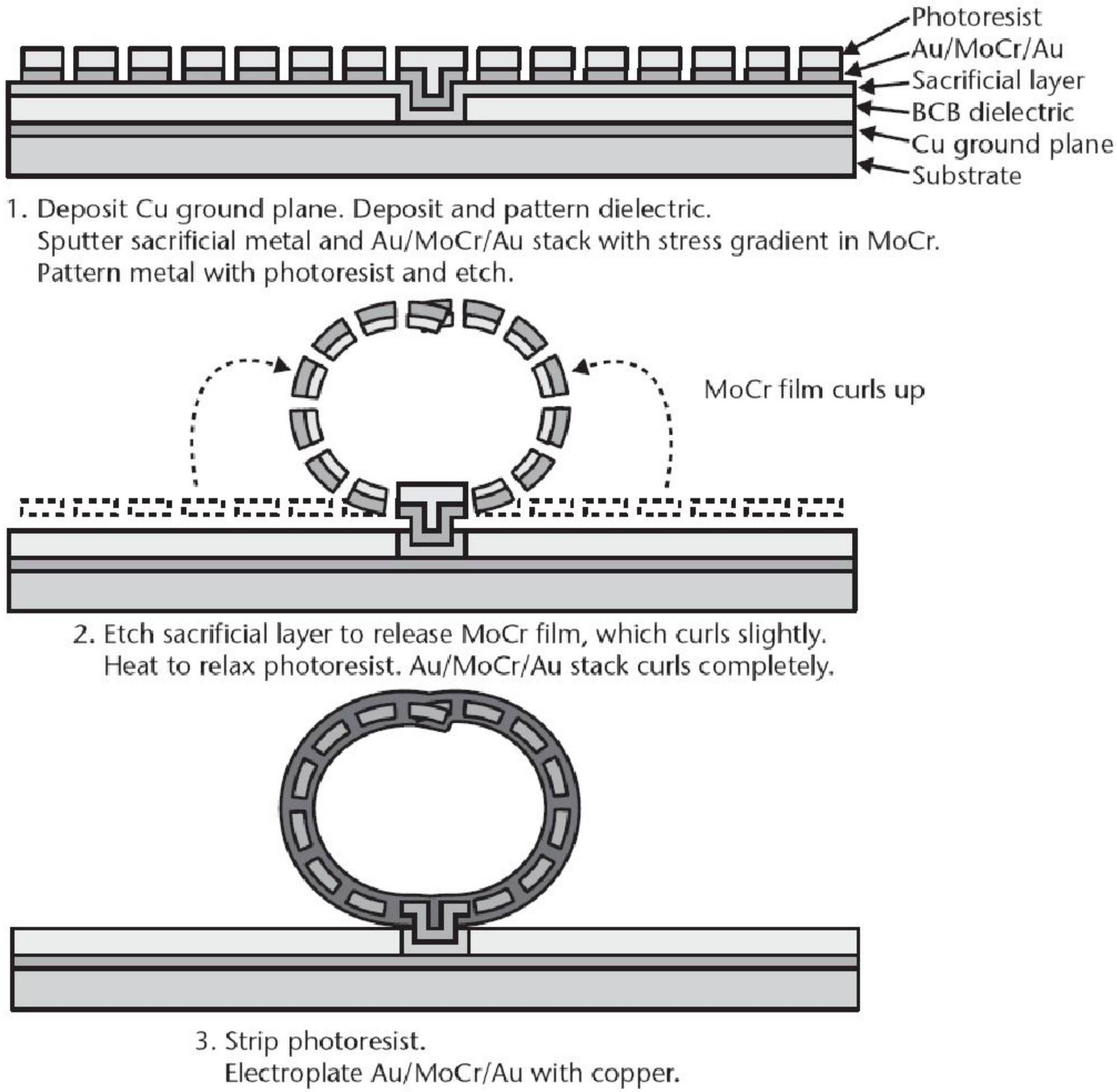
Индуктивность Microinductor



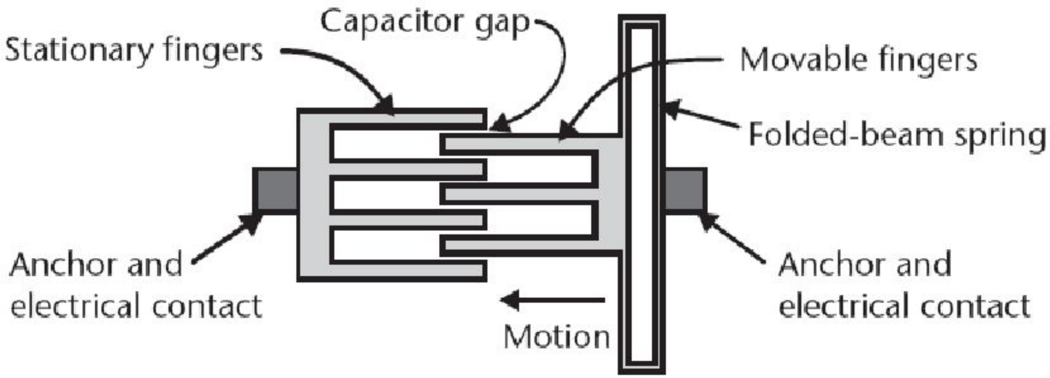
(a) (b)

The PARC inductor: (a) scanning-electron micrograph (SEM) of a five-turn solenoid inductor (the locations of the sides of the turns before release are visible); and (b) SEM close up of the tops of the turns where the metal from each side meets, showing the interlocked ends. The etch holes have been filled with copper.

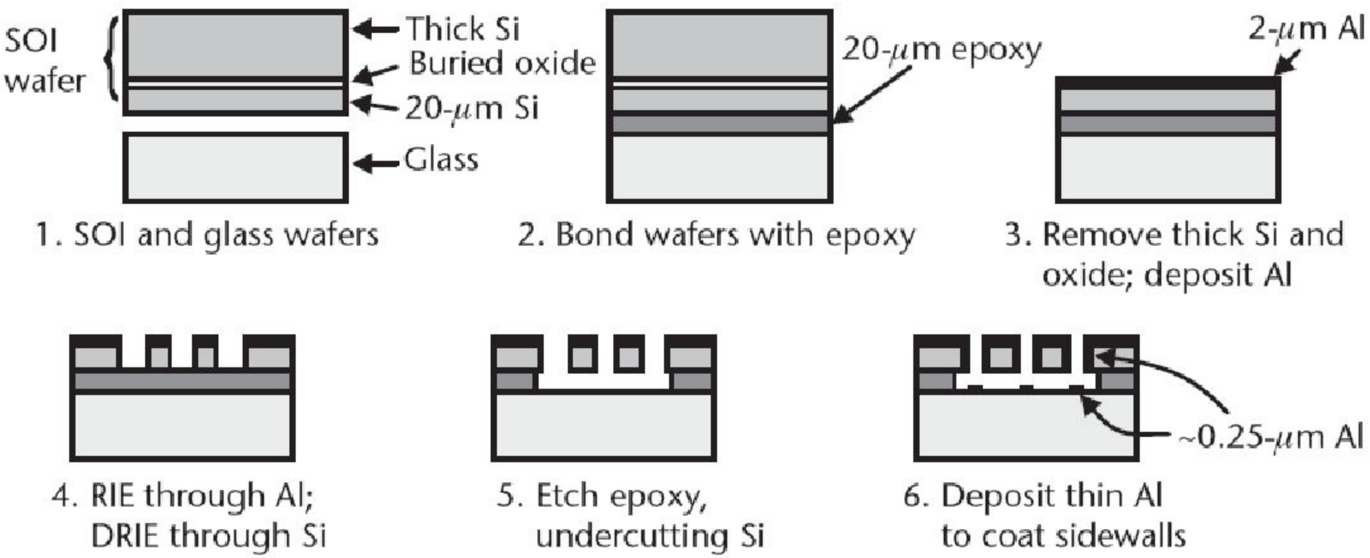
Индуктивность - последовательность производства НЭМС Fabrication of microinductor



Переменная емкость Tunable capacitor

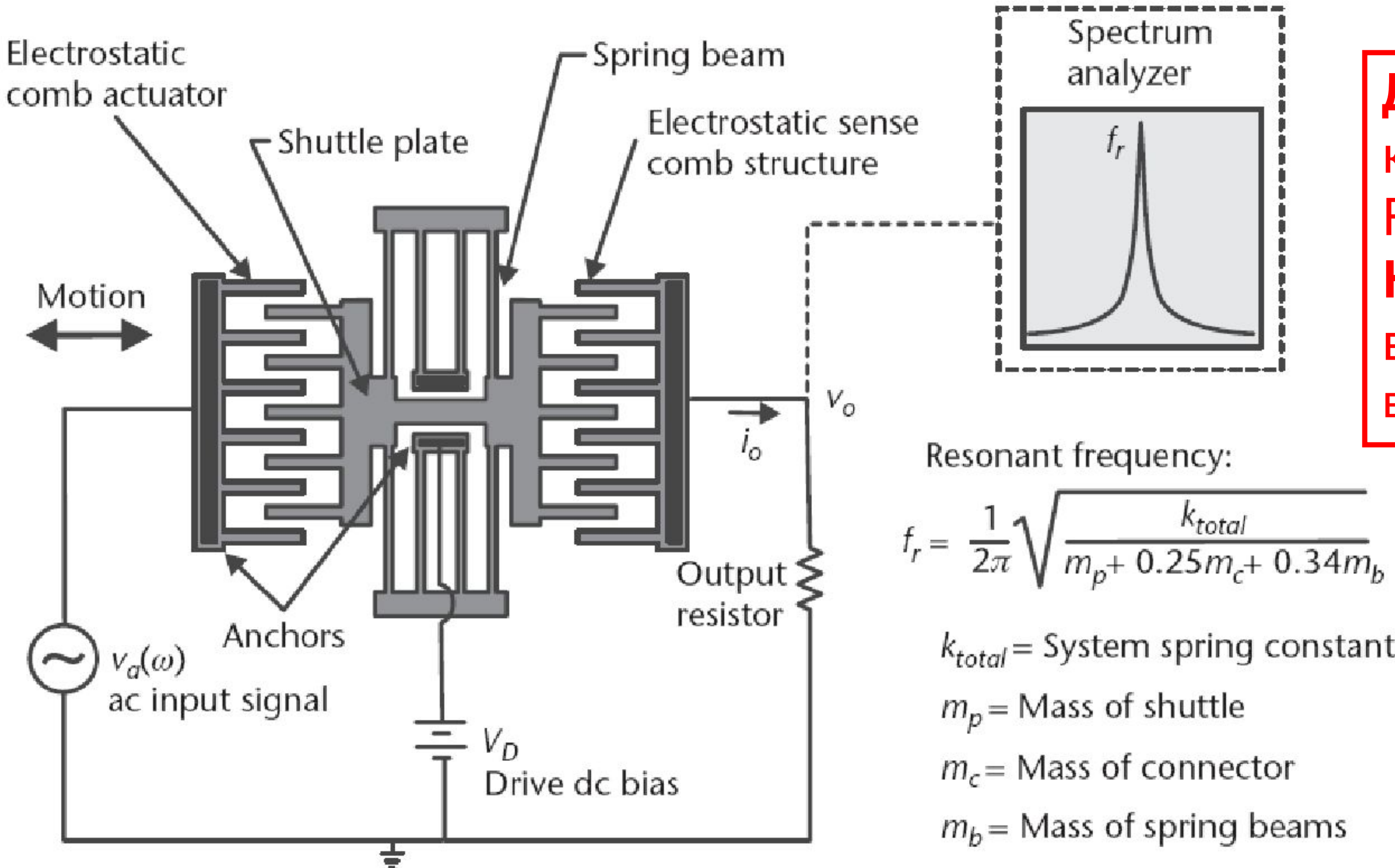


(a)



(b)

Резонатор Resonator

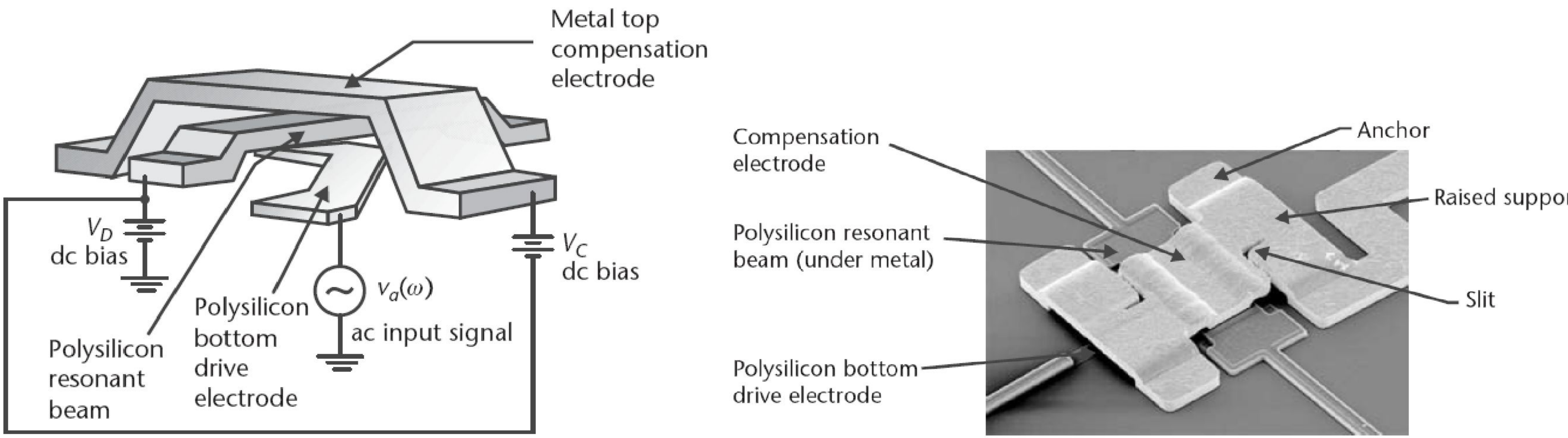


Добротность Q
кварц Q≈10000
RLC Q<1000
НЭМС:
вакуум Q>50000
воздух Q<50

$k = E\,t\,(w/L)^3$
E = 160 GPa
t = 2 μm
w = 2 μm
L = 33 μm
$m = 5.7 \cdot 10^{-11}$ kg
f = 190 kHz

Illustration of a micromachined folded-beam comb-drive resonator. The left comb drive actuates the device at a variable frequency ω. The right capacitive-sense-comb structure measures the corresponding displacement by turning the varying capacitance into a current, which generates a voltage across the output resistor. There is a peak in displacement, current, and output voltage at the resonant frequency.

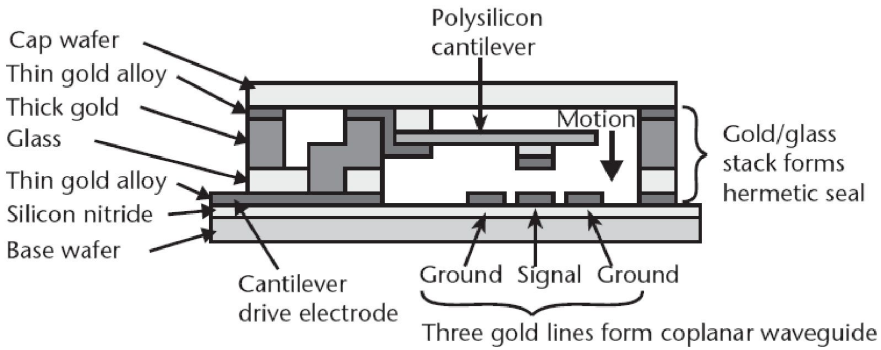
Высокочастотный резонатор с термокомпенсацией
Resonator with thermal compensation

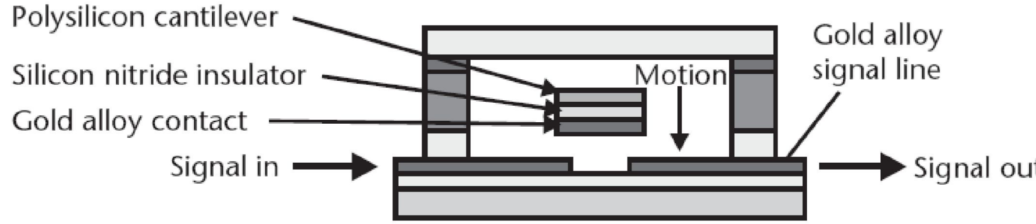


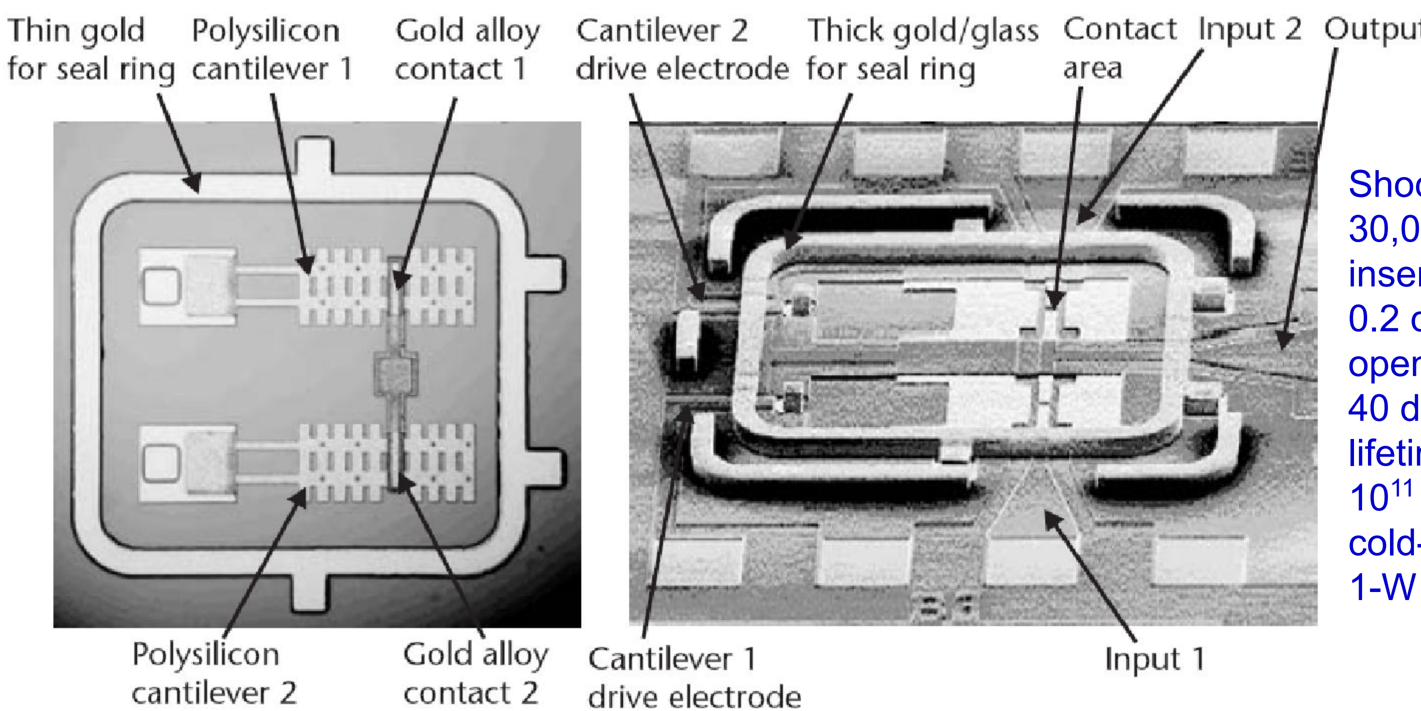
(a) (b)

Illustration of the compensation scheme to reduce sensitivity in a resonant structure to temperature. A voltage applied to a top metal electrode modifies through electrostatic attraction the effective spring constant of the resonant beam. Temperature changes cause the metal electrode to move relative to the polysilicon resonant beam, thus changing the gap between the two layers. This reduces the electrically induced spring constant opposing the mechanical spring while the mechanical spring constant itself is falling, resulting in their combination varying much less with temperature. (a) Perspective view of the structure, and (b) scanning electron micrograph of the device. (*Courtesy of:* Discera, Inc., Ann Arbor, Michigan, USA.)

Переключатель Electric switch



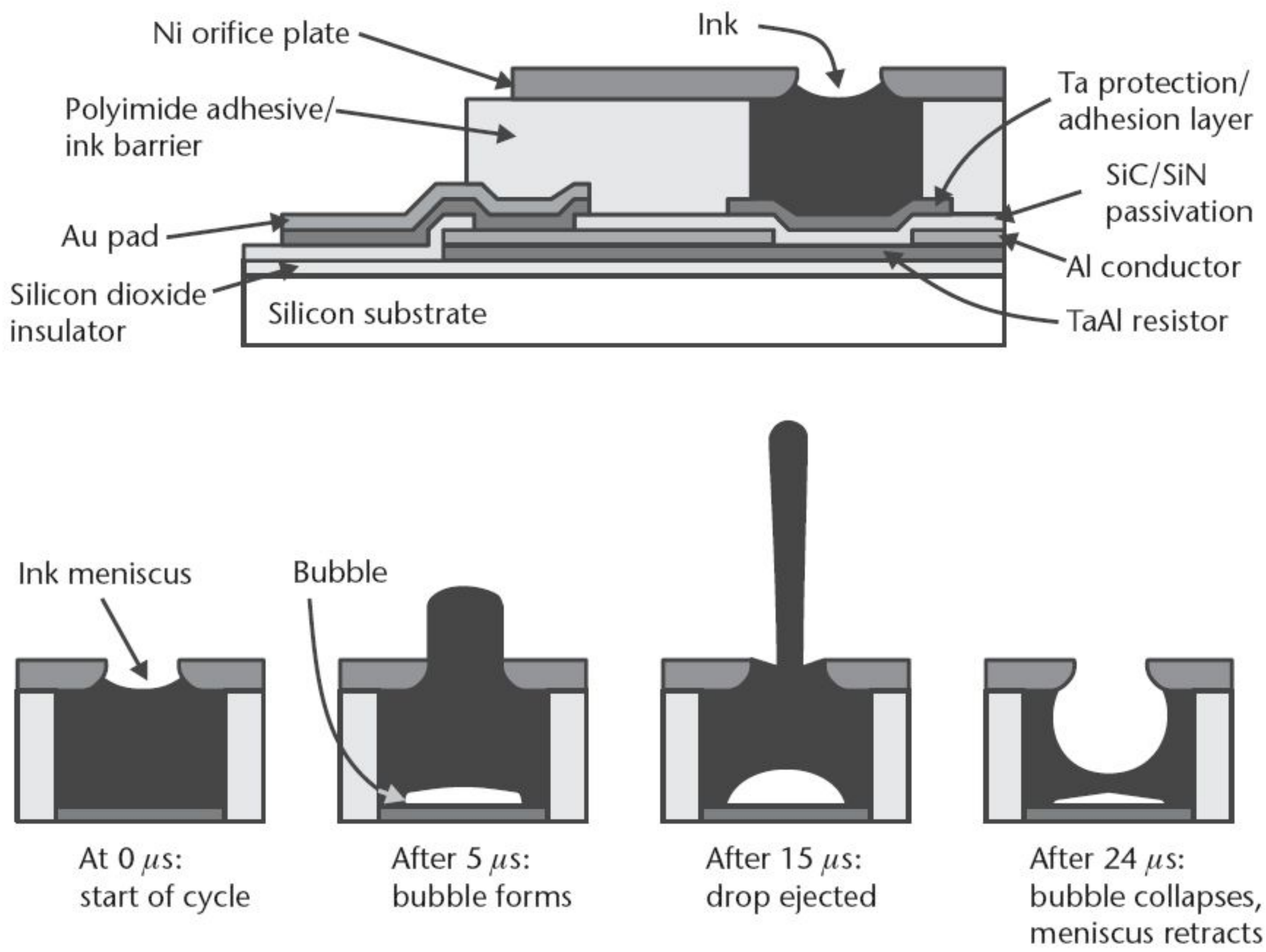




Shock tolerance of 30,000G,
insertion loss of 0.2 dB over 24–40 GHz,
open isolation of 40 dB,
lifetime of 10^{11} cycles,
cold-switched power of 1-W

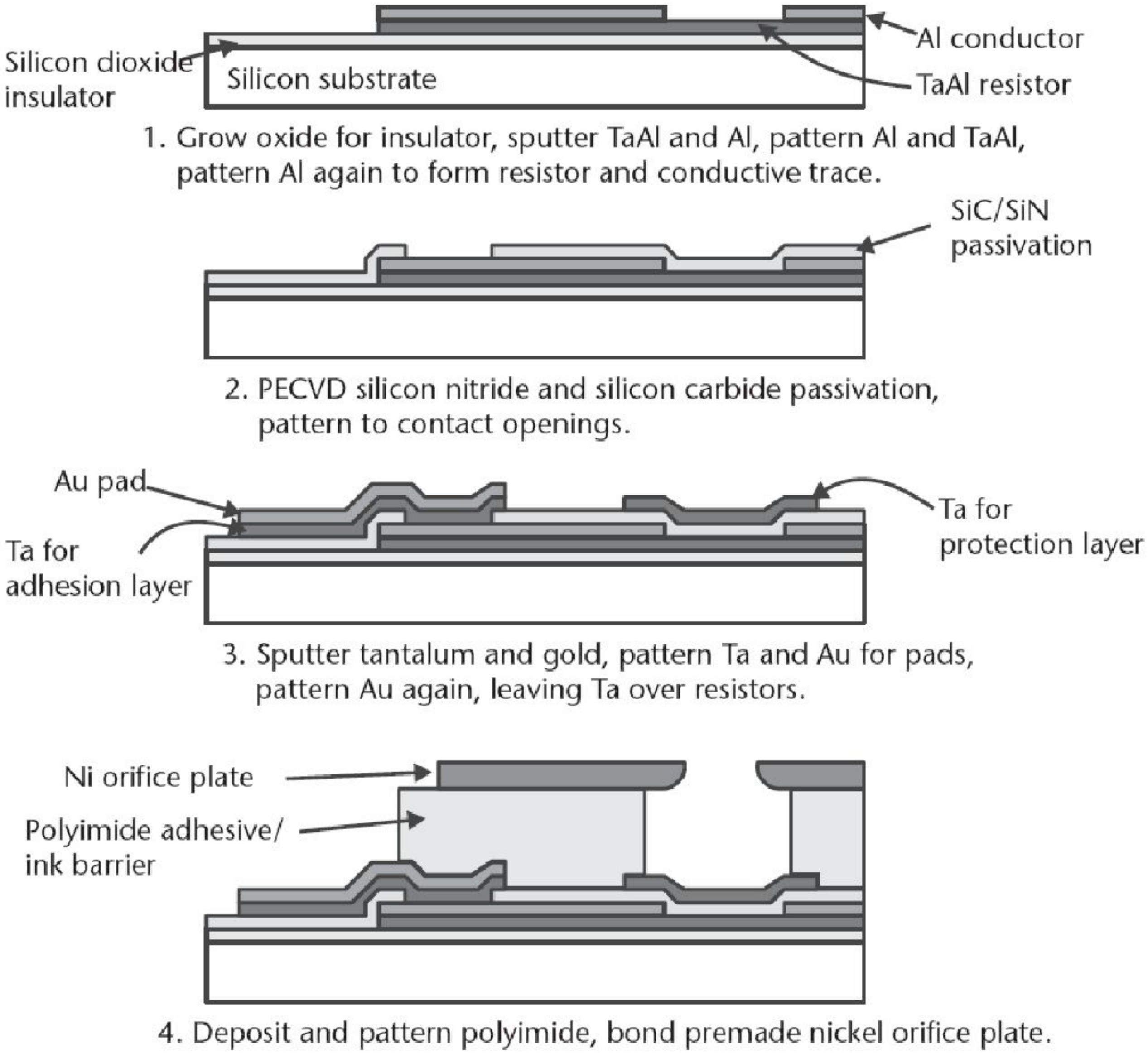
MicroAssembly Technologies of Richmond, California, USA

Головка струйного принтера HP
Head of HP inc-jet printer



Heater temperature 250 °C, peak pressure 1.4 MPa, droplet volume 10^{-10} l.

Головка струйного принтера HP - последовательность производства. Head of HP inc-jet printer - production steps



Головка струйного принтера HP

dpi	Число ячеек в головке
96	12
180	30
300	50
600	104
1200	> 200

Прямое управление каждым элементом

Используется электронная кремниевая микросхема для упрощения управления головкой, удешевления и повышения надежности

.Регуляторы потоков. Microvalves

Области применения:

- Electronic flow regulation of refrigerant for increased energy savings;
- Electronically programmable gas cooking stoves;
- Electronically programmable pressure regulators for gas cylinders;
- Accurate mass flow controllers for high-purity gas delivery systems;
- Accurate drug delivery systems;
- Control of fluid flow in portable biochemical analysis systems;
- Portable gas chromatography systems;
- Proportional control for electrohydraulic braking (EHB) systems.

Нормально-открытый регулятор потока
Normally open microvalve

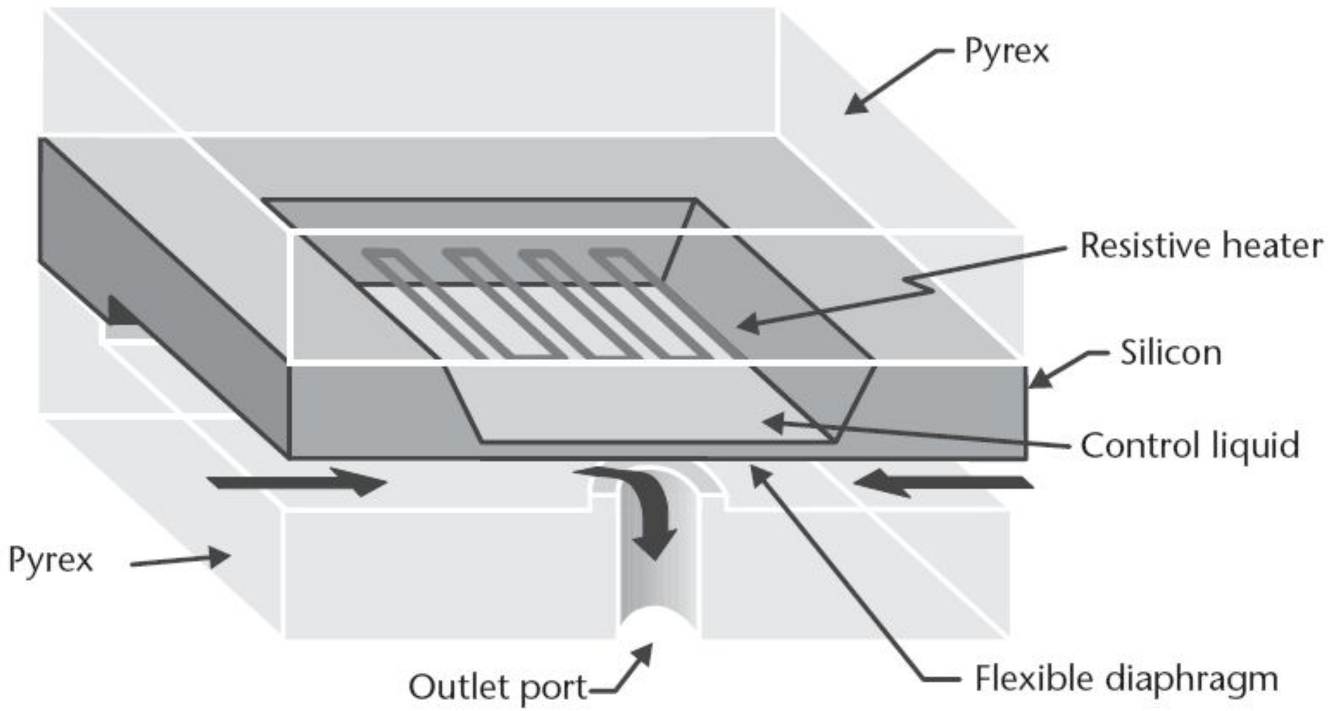


Illustration of a normally open valve from Redwood Microsystems, Ca. Heating of a control liquid sealed inside a cavity causes a thin silicon diaphragm to flex and block the flow through the outlet orifice. The inlet port is not shown.

The flow rate ranges from 0.1 sccm up to 1,500 sccm. The maximum inlet supply pressure is 690 kPa, the switching time is typically 0.5s, and the corresponding average power consumption is 500 mW.

Нормально-закрытый регулятор потока
Normally closed microvalve

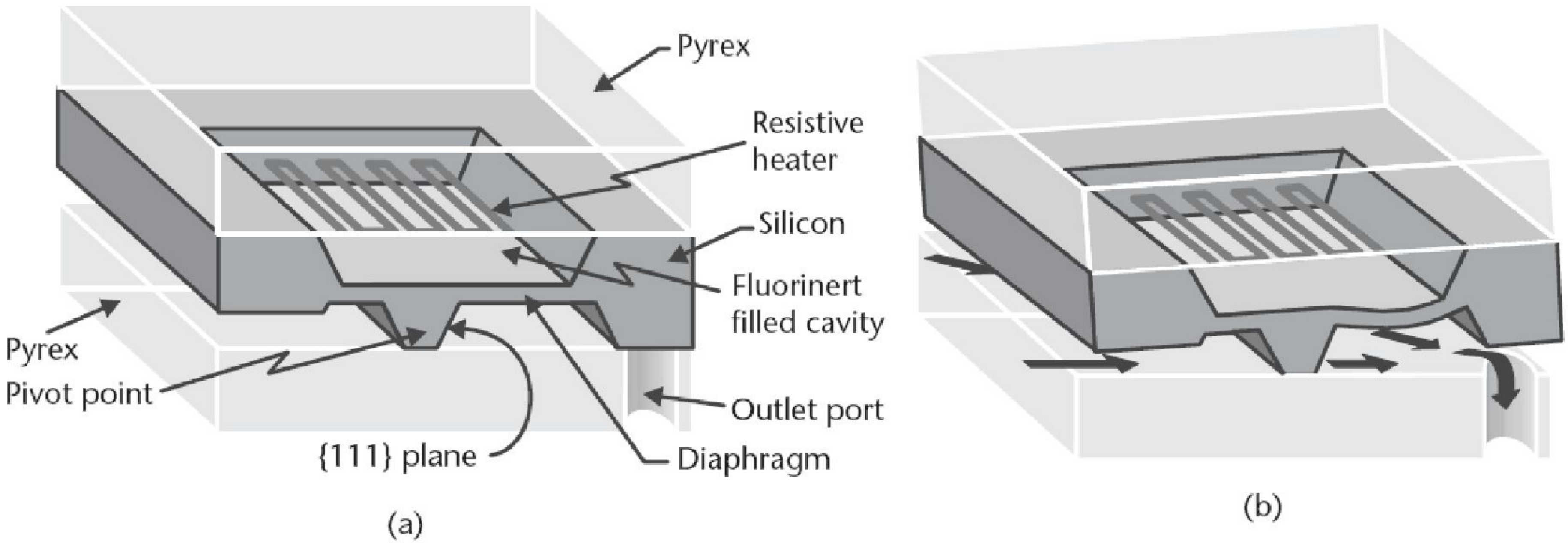
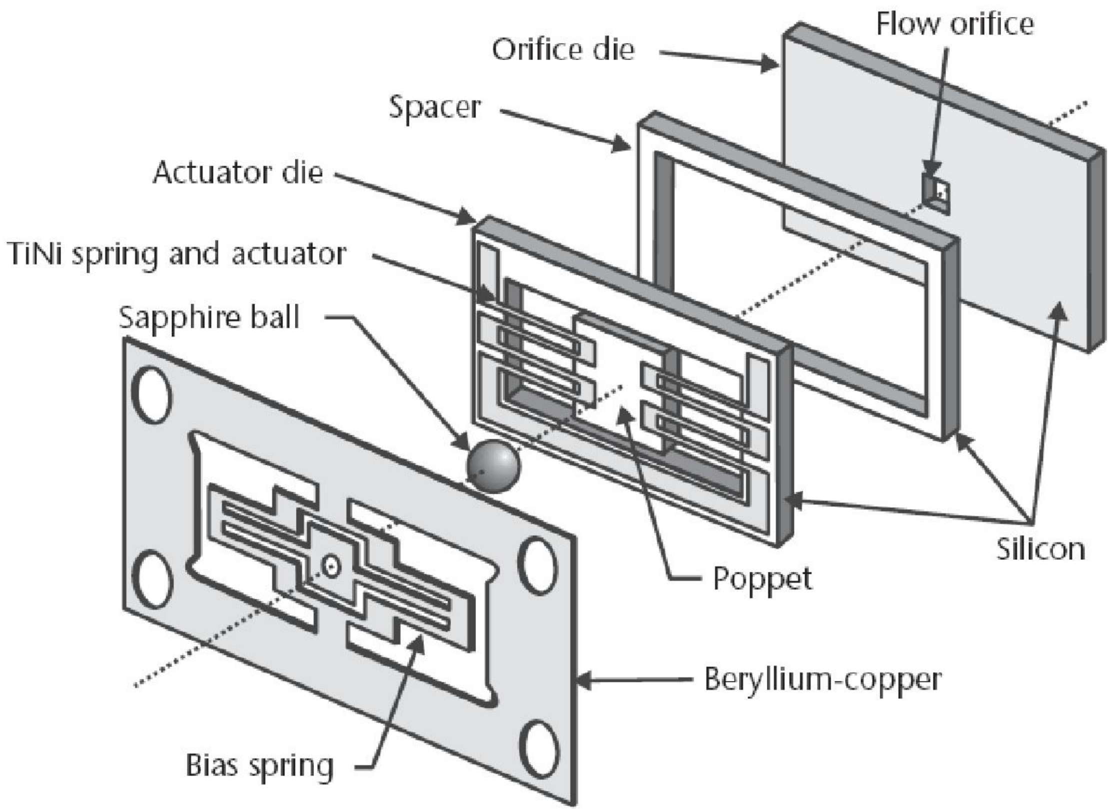


Illustration of the basic operating mechanism of a normally closed micromachined valve from Redwood Microsystems. (a) The upper stage of the valve normally blocks fluid flow through the outlet orifice. The inlet orifice is not shown. (b) Heating of the Fluorinert liquid sealed inside a cavity flexes a thin silicon diaphragm which in turn causes a mechanical lever to lift the valve plug.

Ограничения регулятора потока с термо-пневматическим приводом

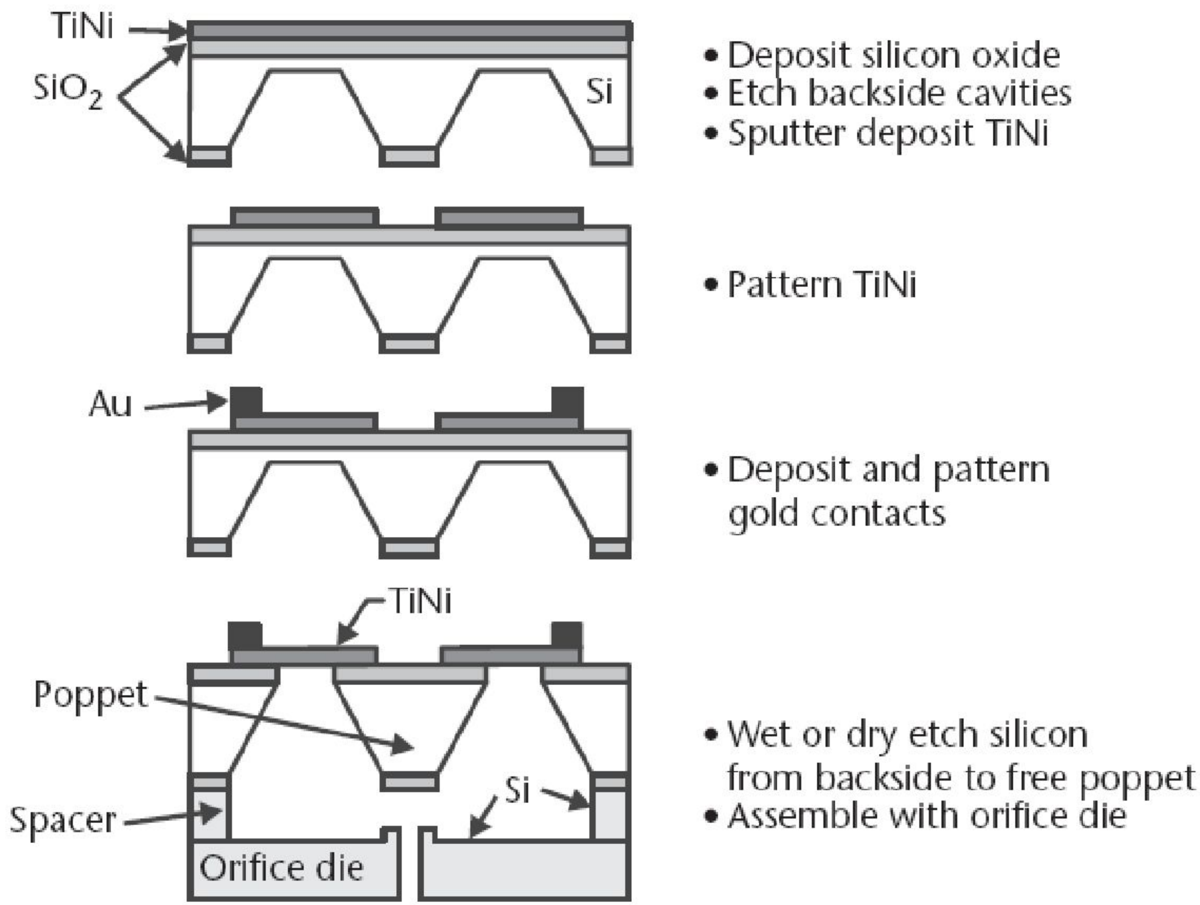
- Утечка тепла Leak of heat
- Скорость переключения Switching time
- Предельное давление Pressure limit
- Влияние температуры окружающей среды Ambient temperature dependence
- Влияние давления протекающей жидкости Pressure of liquid flow
- Коррозия Corrosion

Микроклапан с приводом из металла с памятью формы
Normally closed valve with shape-memory-alloy actuator



Assembly of the micromachined, normally closed valve with TiNi alloy actuator. The beryllium-copper spring pushes a sapphire ball against the silicon poppet to close the flow orifice. Resistive heating of the TiNi spring above its transition temperature causes it to recover its original flat (undeflected) shape. The actuation pulls the poppet away from the orifice, hence permitting fluid flow. (After: A. D. Johnson, TiNi Alloy Company of San Leandro, California.)

Микроклапан – последовательность изготовления привода Normally closed valve with TiN actuator – production steps



The valve consumes less than 200 mW and switches on in about 10 ms and off in about 15 ms. The maximum gas flow rate and inlet pressure are 1,000 sccm and 690 kPa (100 psig), respectively. The valve measures 8 mm × 5 mm × 2 mm and is assembled inside a plastic package. The list price for one valve is about $200.

Микронасос Micropump

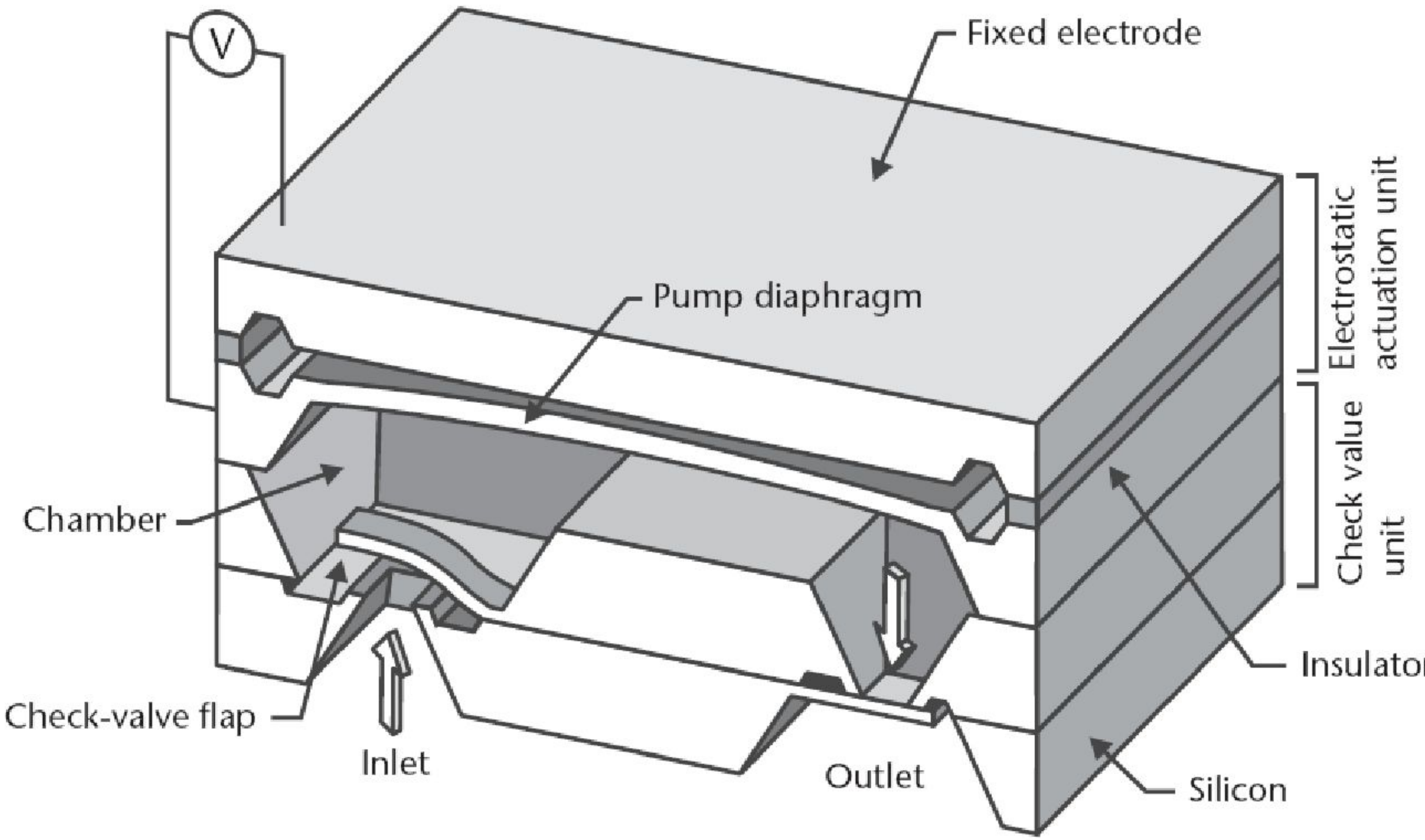
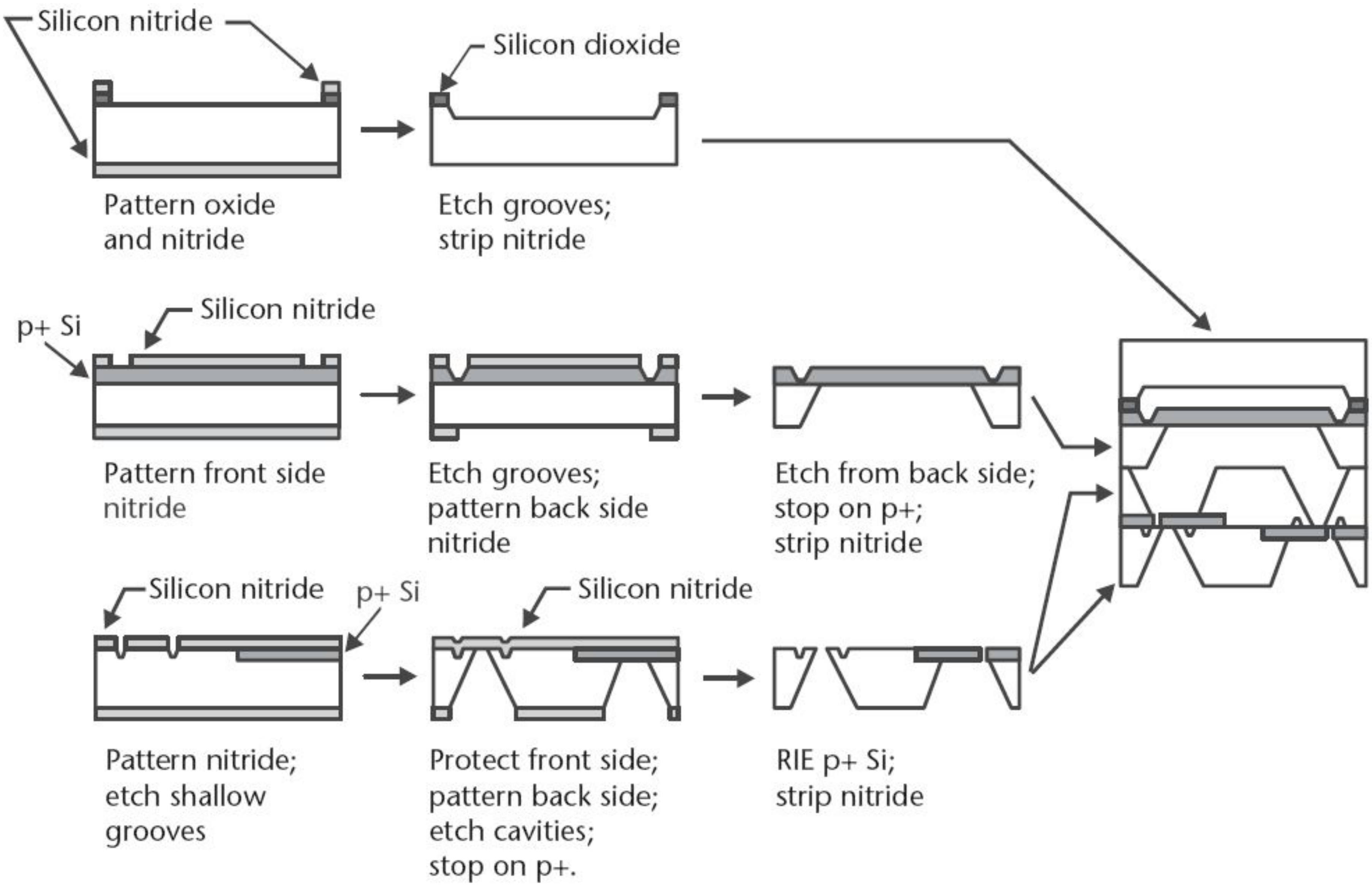
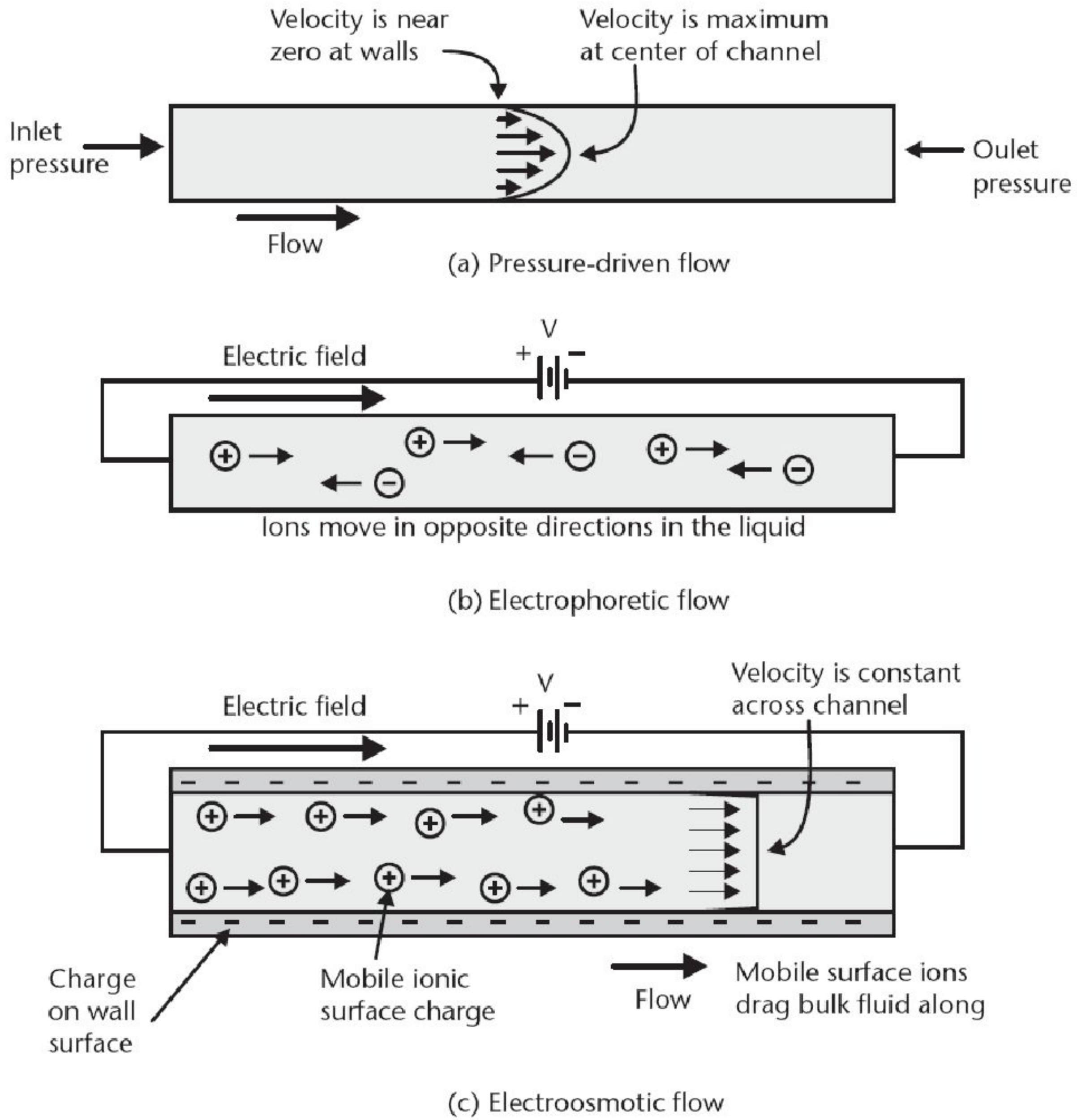


Illustration of a cutout of a silicon micropump from the Fraunhofer Institute for Solid State Technology of Munich, Germany. The overall device measures 7 x 7 x 2 mm^3. The electrostatic actuation of a thin diaphragm modulates the volume inside a chamber. An increase in volume draws liquid through the inlet check valve. Relaxation of the diaphragm expels the liquid through the outlet check valve. The pump rate initially rises with frequency and reaches a peak flow rate of 800 µl/min at 1 kHz.

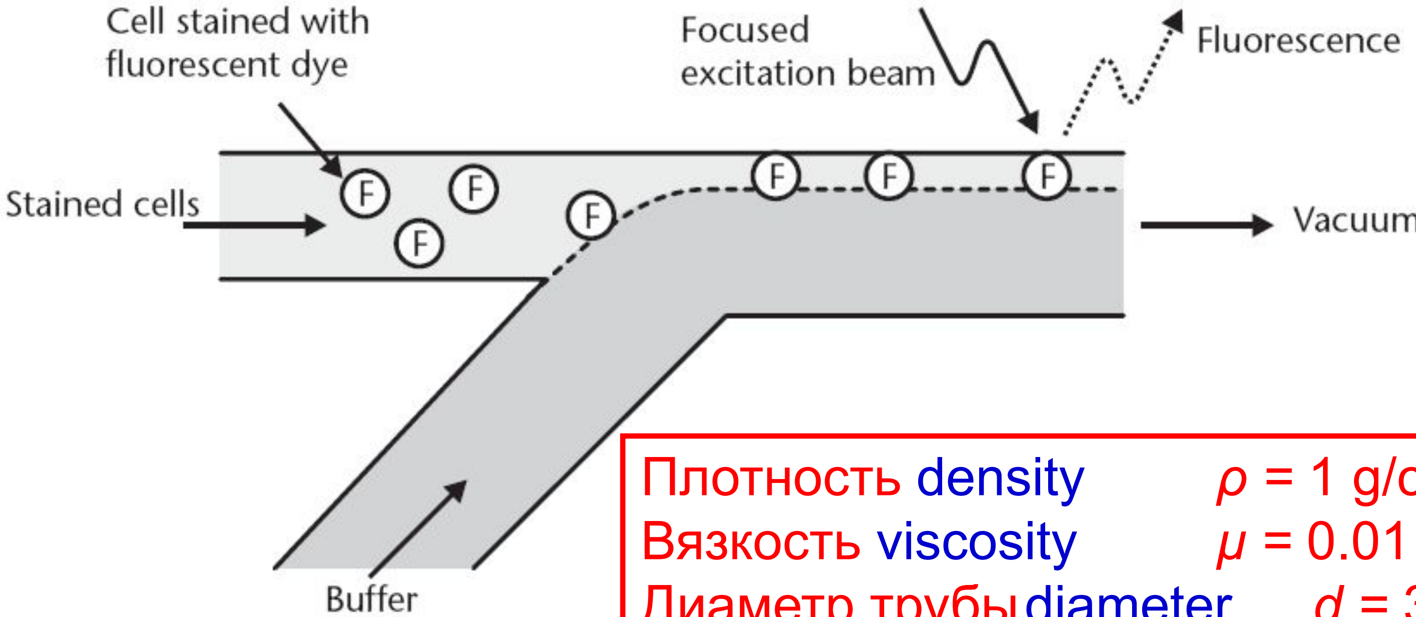
Микронасос - последовательность производства НЭМС



Микрожидкостные системы Microfluidic systems



Смешивание в микроканалах Laminar flow and mixing



Плотность density $\rho = 1$ g/cm

Вязкость viscosity $\mu = 0.01$ g/(cm s)

Диаметр трубы diameter $d = 30$ μm

Скорость потока flow rate $v = 1$ mm/s

Число Рейнолдса $R = \rho\, v\, d\, /\, \mu = 0.03$

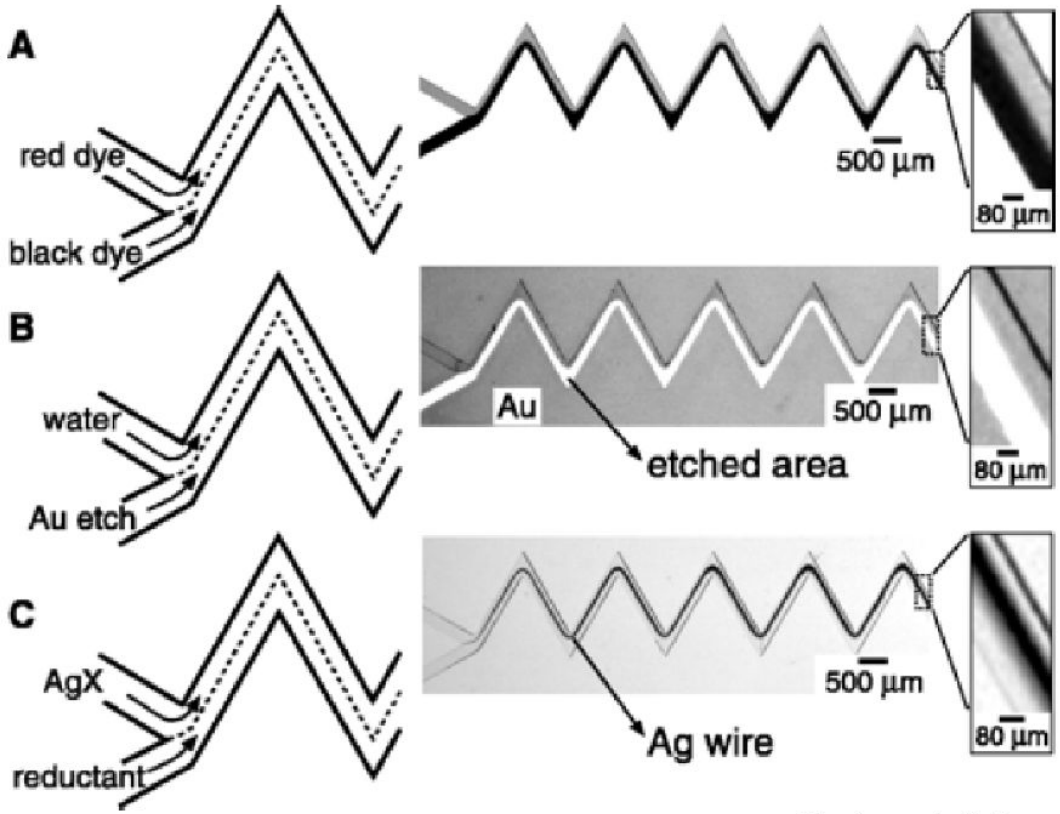
Reynolds number

Критическое Critical $R_c = 2300$

Example of the use of laminar flow in microfluidics: In the Cell LabChip from Agilent Technologies of Palo Alto, California, the flow of cells tagged with a fluorescent dye is pushed to one side of the channel. Individual cells are detected when they fluoresce.

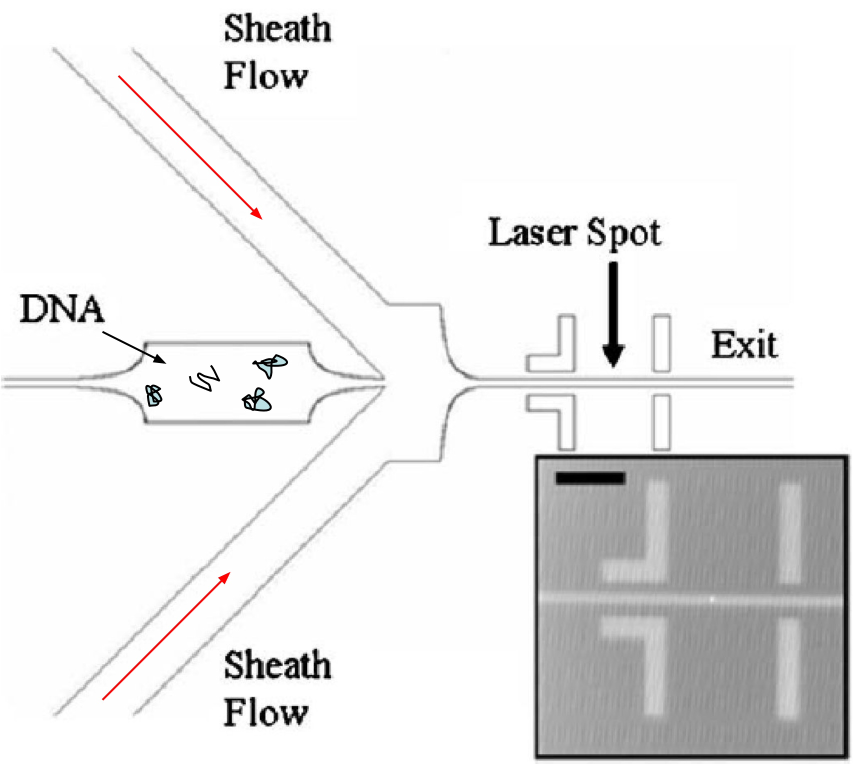
Смешивание в микроканалах Mixing in microchannels

Very low Reynolds numbers = extremely laminar flow.



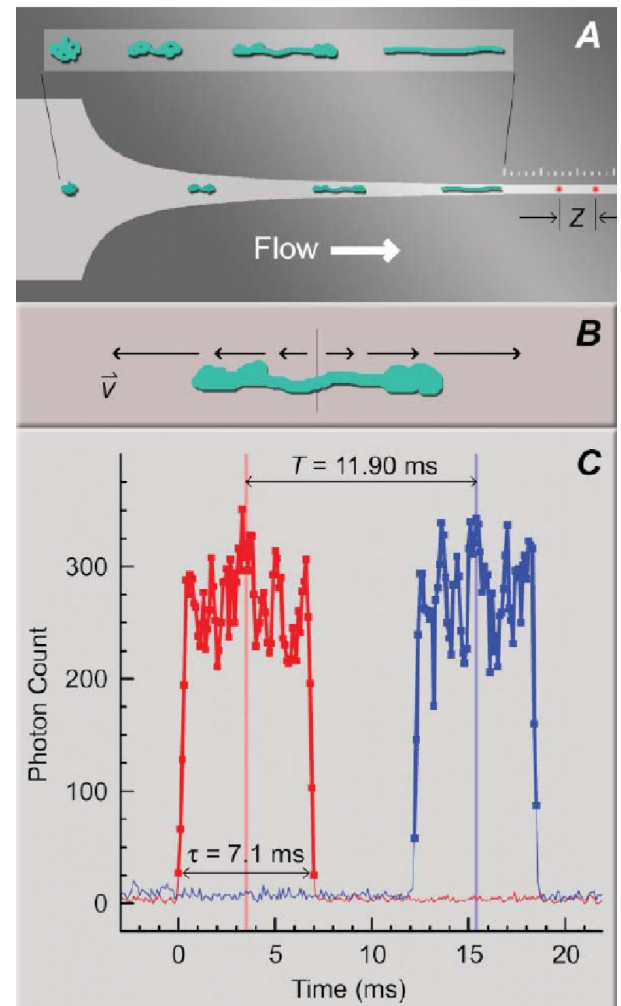
Kenis *et al.*, Science **285**, 83 (1999)

Анализ ДНК - Lab on a Chip DNA analysis



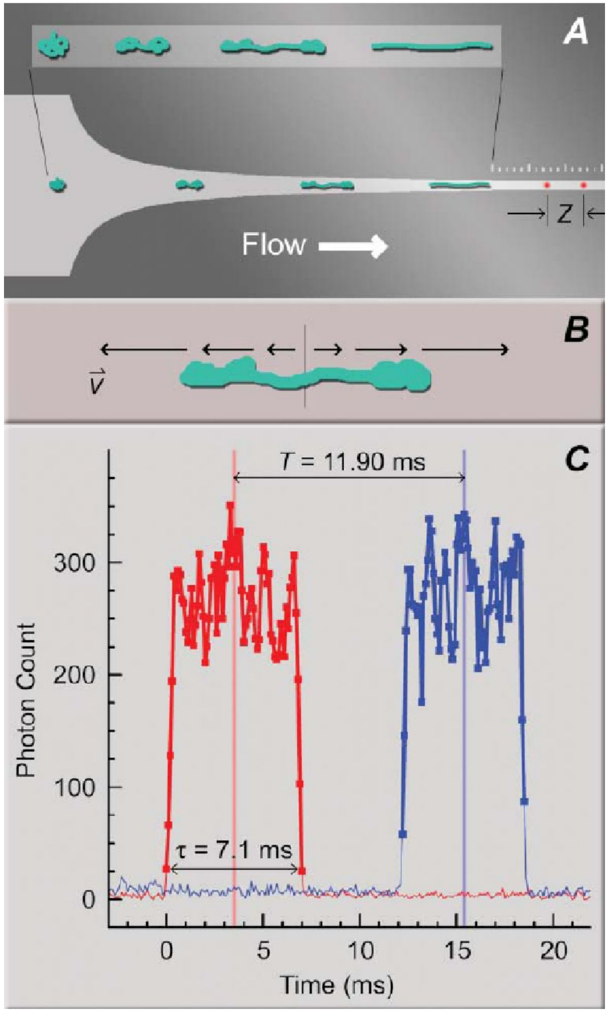
3’CAGTACGTCCAGCTGAGAC5’...

Bar code | | | | |



Schematic of the microfluidic device. The device incorporates a two-dimensional, hydrodynamic flow focusing design for stretching individual l-phage DNA molecules. The sample is inserted into the DNA port (left side) along with 1X TE buffer into each of the sheath flow ports (top, bottom). Sample flow is from left to right. Inset: image of the laser spot positioned in the backlit microfluidic channel. The microfluidic channel is 5 mm wide in the interrogation region highlighted by the alignment fiducials on either side of the channel. Bar represents 25 mm. (Krogmeier, 2007)

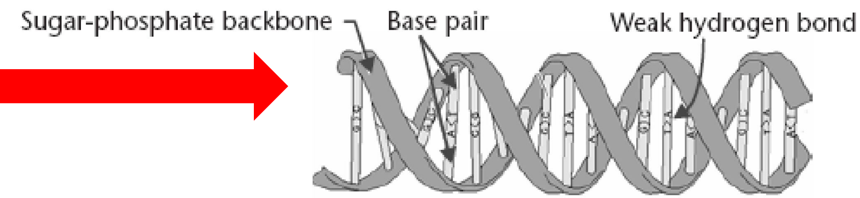
Анализ ДНК

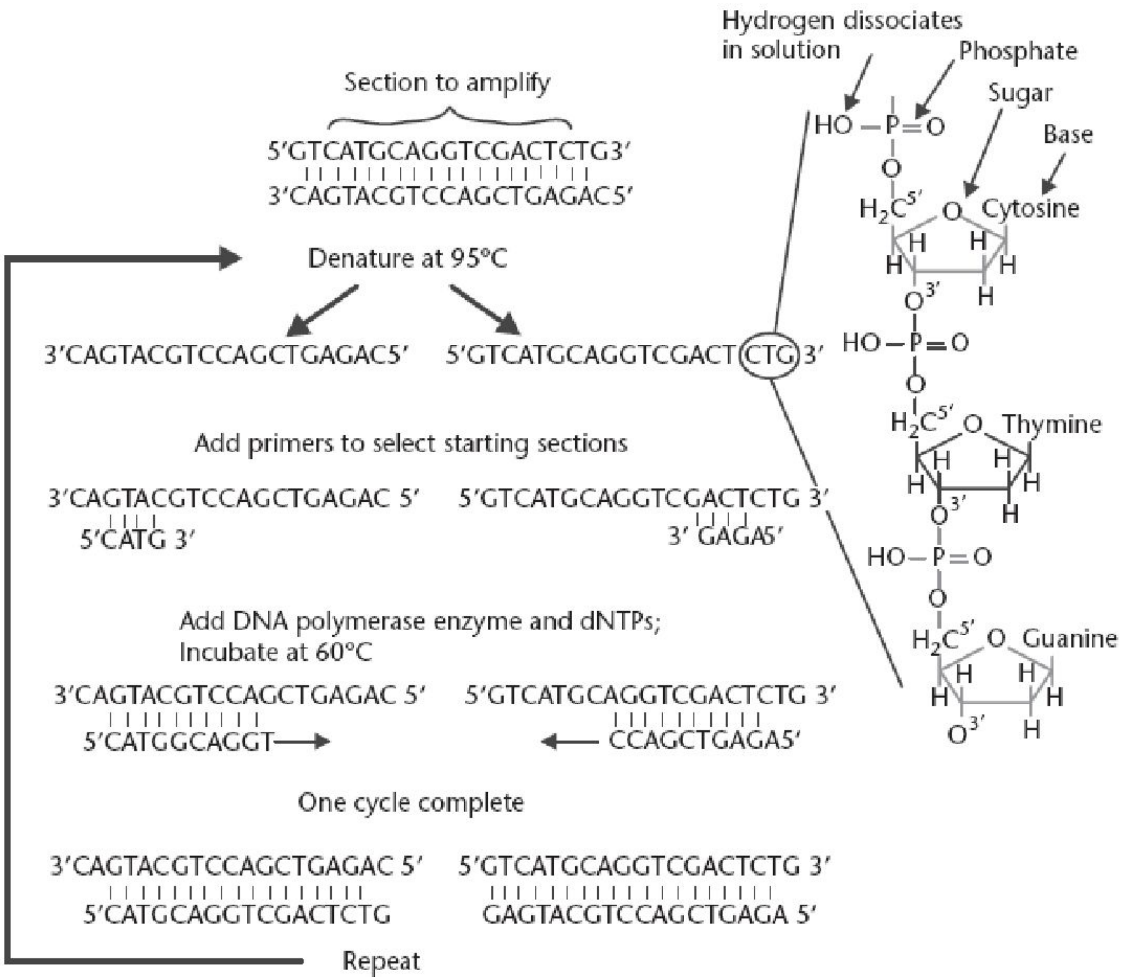


Two-spot system for interrogating DNA conformations after stretching in mixed microflows. (A) CAD drawing of a funnel for high strain rate flows similar to those used in this study (constant strain rate design, wi = 50 mm, wf = 2.5 mm, lF = 125 mm), with a superimposed cartoon of DNA responding to the elongational component of the flow. The inset is provided for clarity. The constant width exit channel begins at the first tick mark on the ruler etched above the funnel (10 mm and 2 mm between major and minor tick marks, respectively). The two confocal spots for DNA fluorescence detection (red spots in the exit channel), separated by a distance, Z, are aligned at one contour length of the longest polymer in a mixture away from the end of the funnel. (B) Cartoon of DNA stretching in a pure elongational flow with a strong velocity gradient (equivalently, strain rate) along the polymer. (C) Example single DNA molecule detection event. Two similar fluorescence bursts from the separate confocal detection spots (red and blue traces for the first and second spots away from the funnel, respectively), with CMs marked as vertical lines, were separated by time T, indicating DNA velocity. Thick lines with symbols denote the contiguous region above a threshold value. The burst duration, t, reveals the length of the molecule in the projection of flow. Z = 28 mm for this example.

Синтез ДНК DNA synthesis

Twisted double-helix structure of DNA

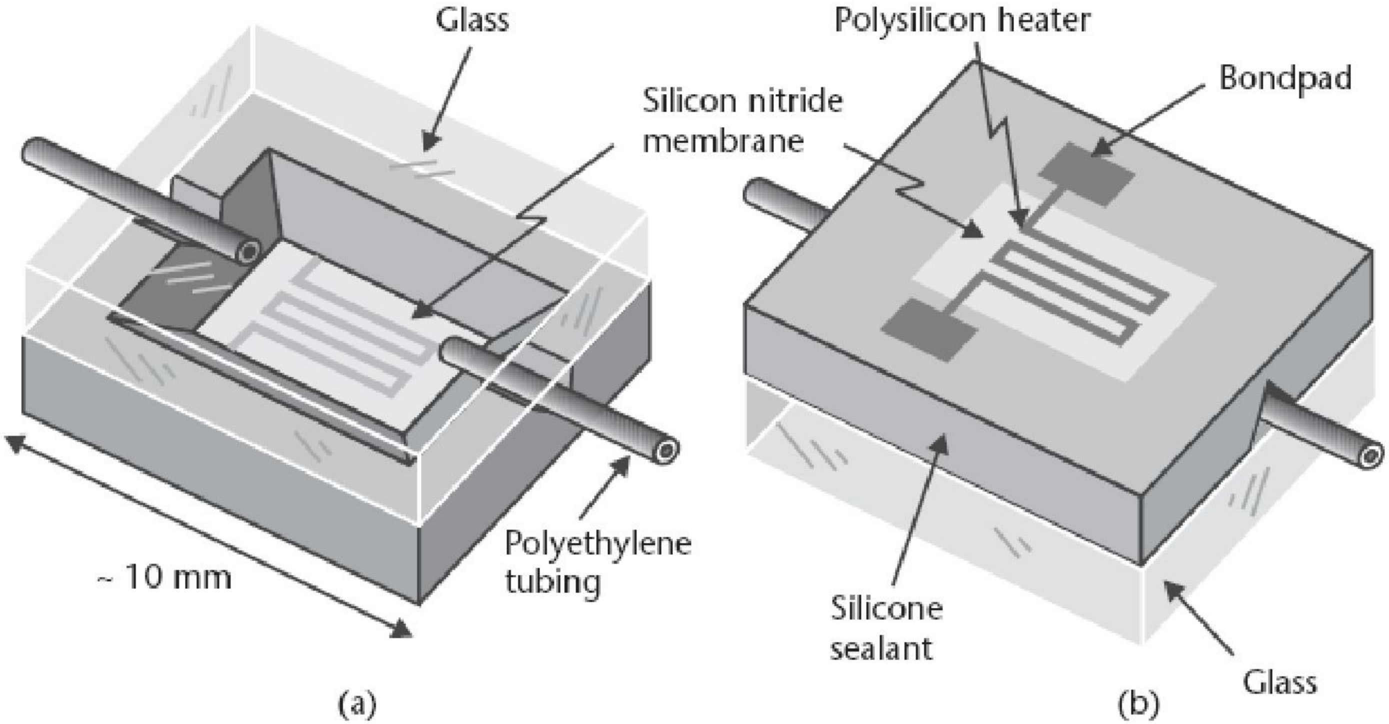




Polymerase chain reaction (PCR).

Denaturing of the starting DNA template at 95ºC yields two strands, each containing all of the necessary information to form a complementary replica. The addition of primers defines the starting point for replication. At 60ºC, the DNA polymerase enzyme catalyzes the reconstruction of the complementary DNA strand from an ample supply of nucleotides (dNTPs). The reconstruction always proceeds in the 5’→3’ direction. The cycle ends with copies of two portions of the helices, in addition to the starting template. The cycle is then repeated. The exploded view of three nucleotides (CTG) in the denatured template shows their chemical composition, including the 3’-hydroxyl and 5’-phosphate groups.

Цепная реакция полимеразы в МЭМС
Polymerase chain reaction in MEMS



Illustrations of (a) the front side, and (b) the back side of an early micromachined silicon PCR chamber. A polysilicon heater on a silicon nitride membrane cycles the solution between the denaturing and incubation temperatures of PCR.

Электрофорезная сортировка ДНК
Electrophoresis system for DNA separation

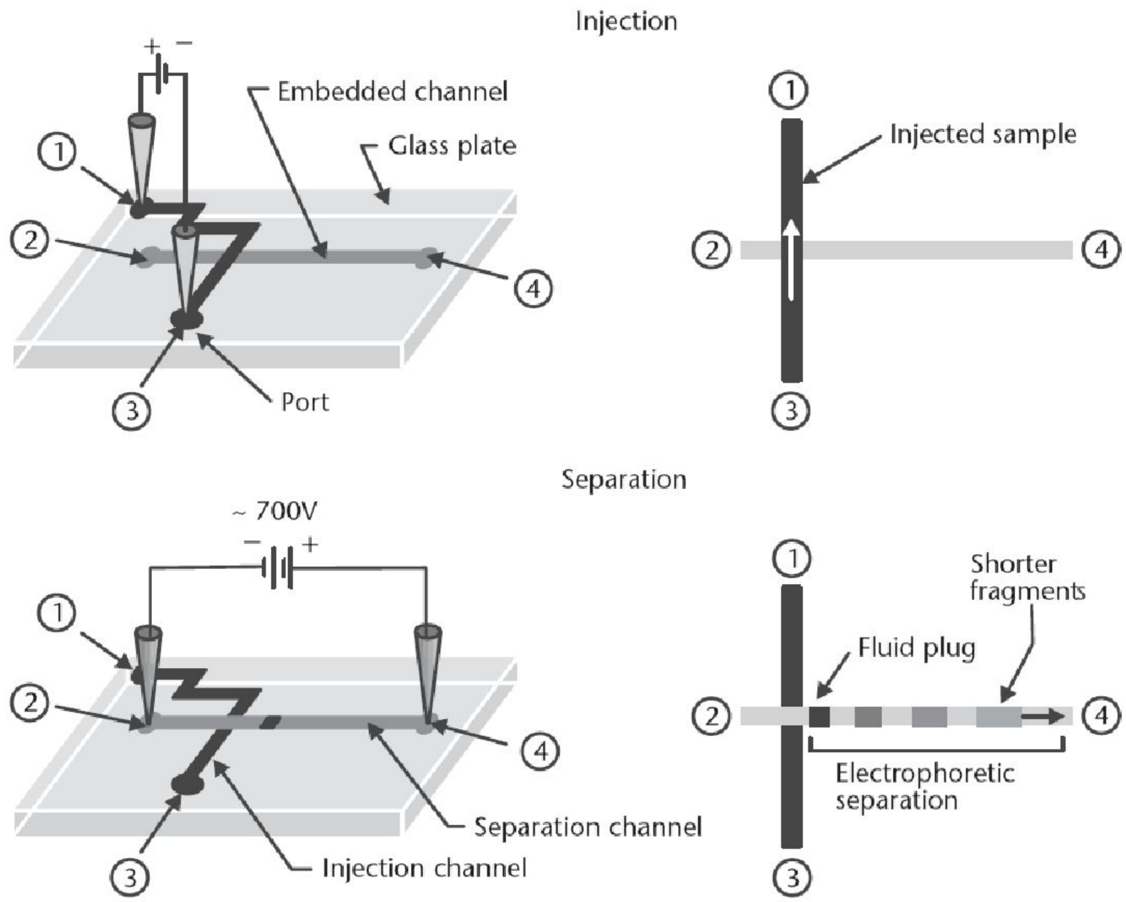
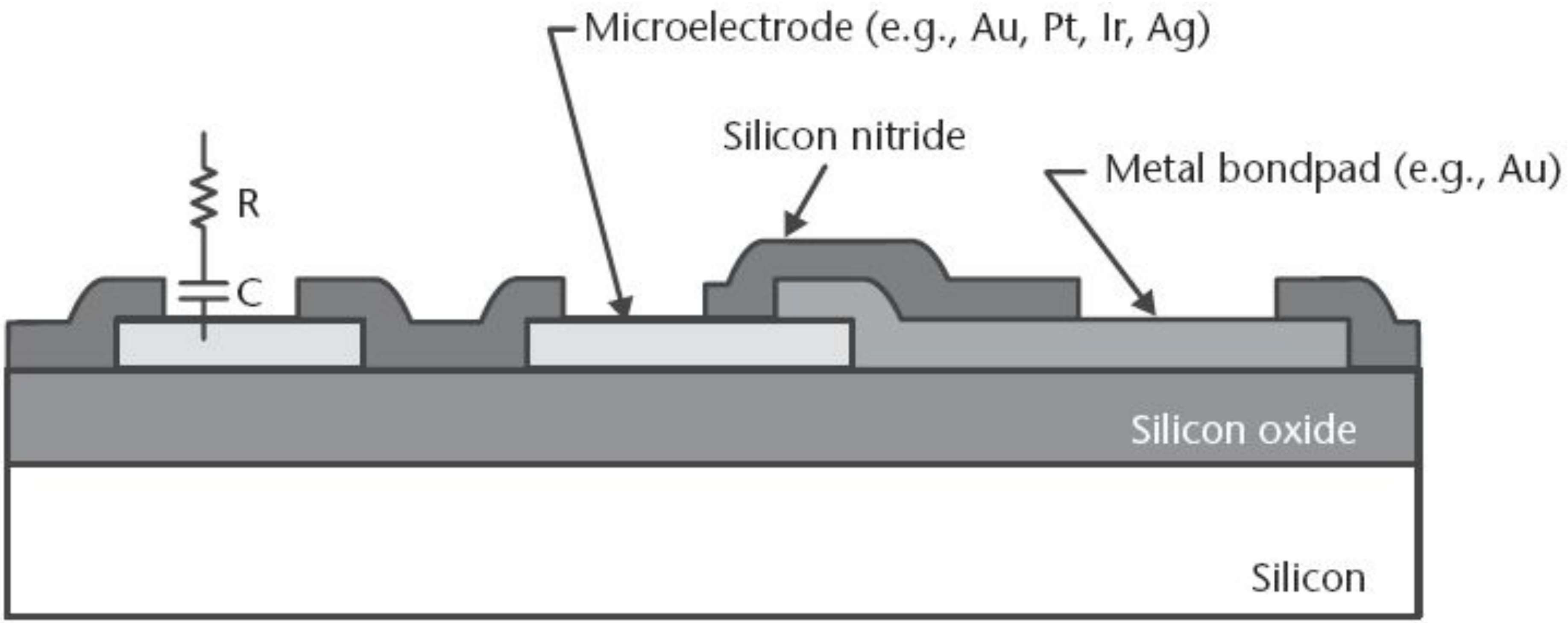


Illustration of the fluid injection and separation steps in a miniature DNA electrophoresis system. An applied electric field electrophoretically pumps the fluid molecules from port 3 to port 1 during the injection step. Another applied voltage between ports 2 and 4 initiates the electrophoretic separation of the DNA molecules. The smearing of the fluid plug in the separation channel is schematically illustrated. The capillary channels have a typical cross section of 8 x 50 μm^2. The separation capillary is 3.5 cm long.

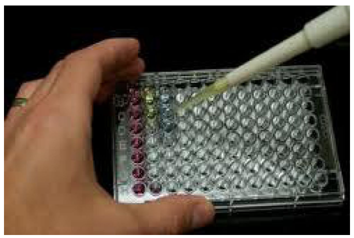
Микроэлектроды Microelectrode array

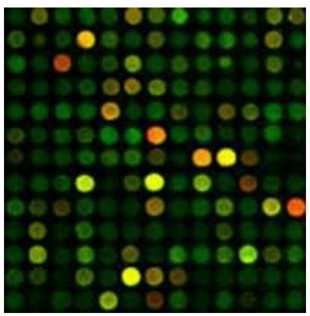


Cross section of a microelectrode array showing two different metals for the electrodes and for the bond pads. The schematic also illustrates a basic electrical equivalent circuit that emphasizes the capacitive behavior of a microelectrode. The silicon substrate and the silicon dioxide dielectric layer may be substituted by an insulating glass substrate.

Анализ ДНК DNA analysis

массив микроэлектродов





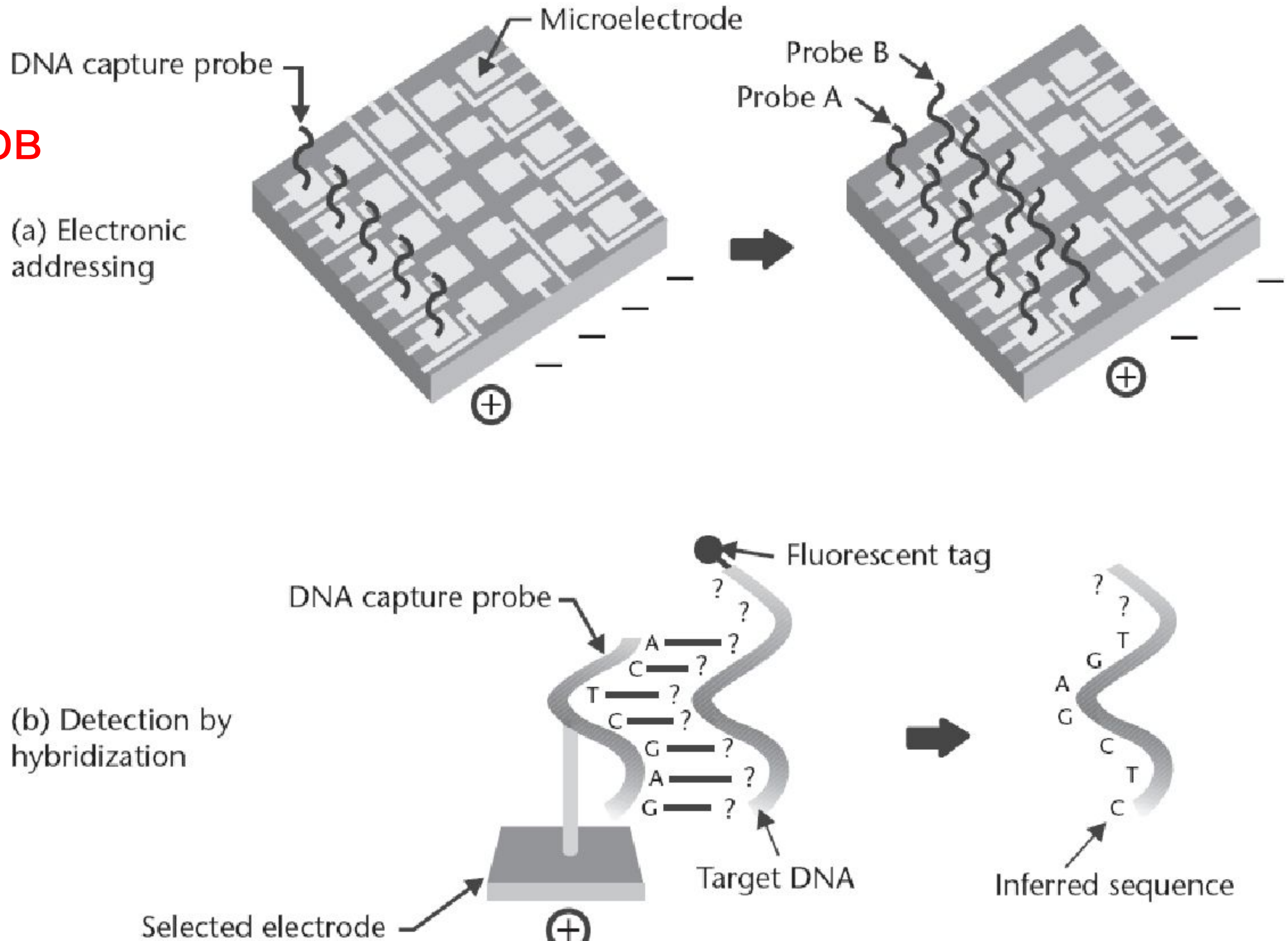
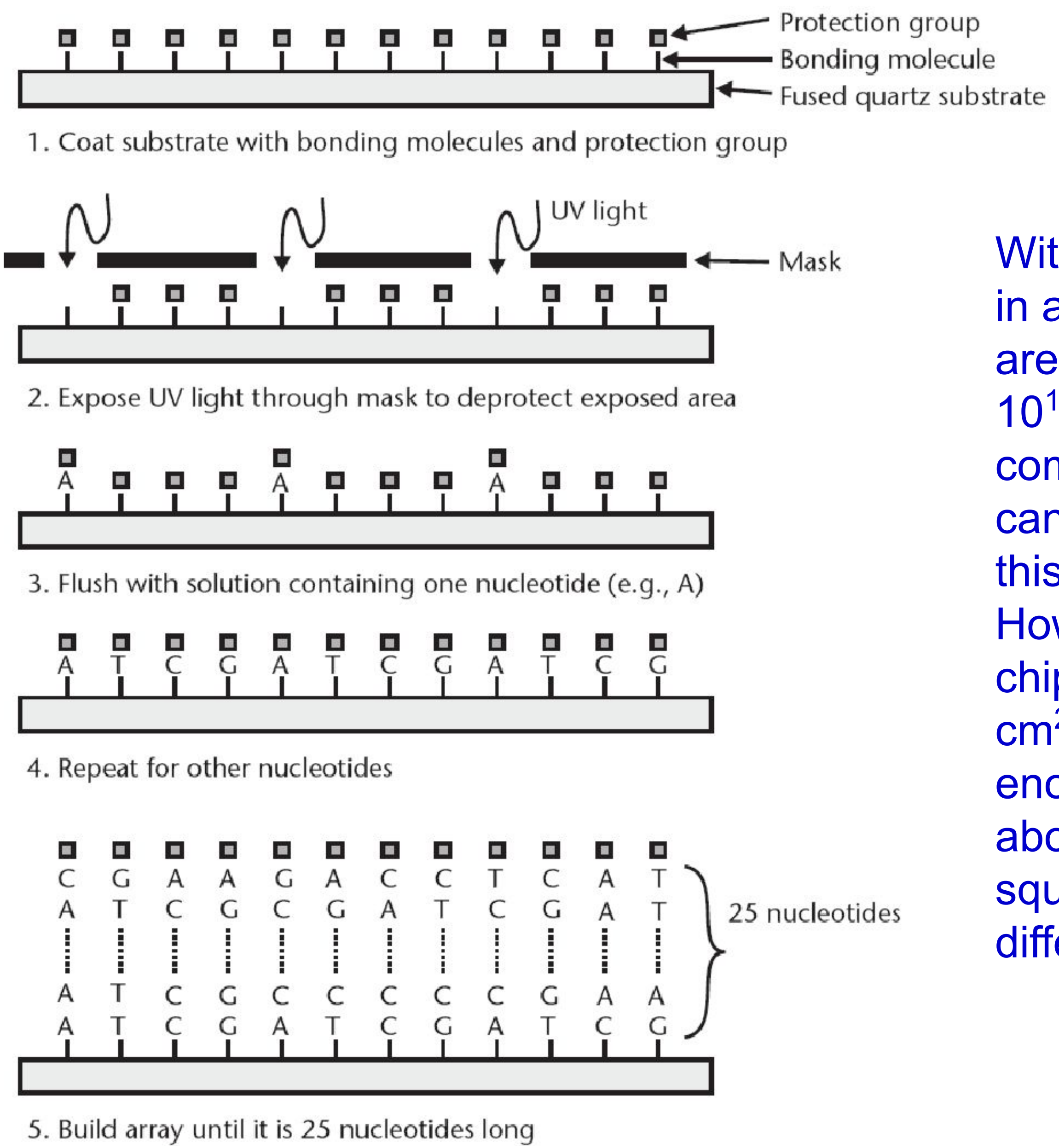


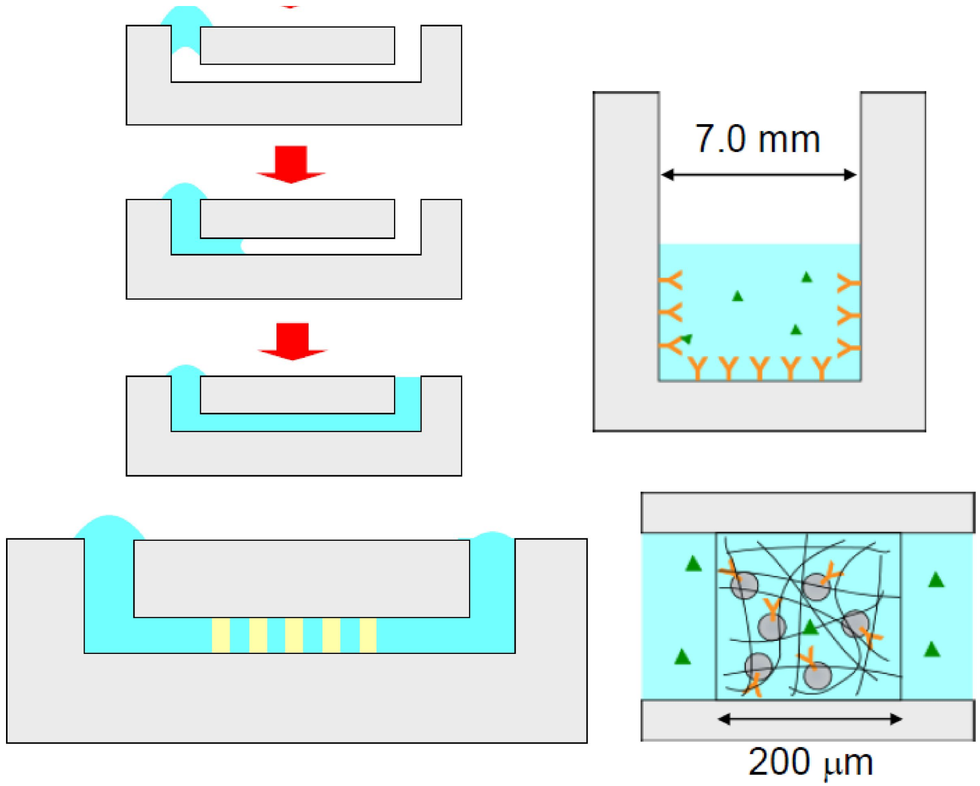
Illustration of the Nanogen electronic addressing and detection schemes. (a) A positive voltage attracts DNA capture probes to biased microelectrodes. Negatively biased electrodes remain clear of DNA. Repetition of the cycle in different solutions with appropriate electrode biasing sequentially builds an array of individually distinct sites of DNA capture probes that differ by their sequence of nucleotides. (b) A DNA fragment with unknown sequence hybridizes with a DNA capture probe with a complementary sequence. Fluorescence microscopy reveals the hybridized site and, consequently, the unknown sequence.

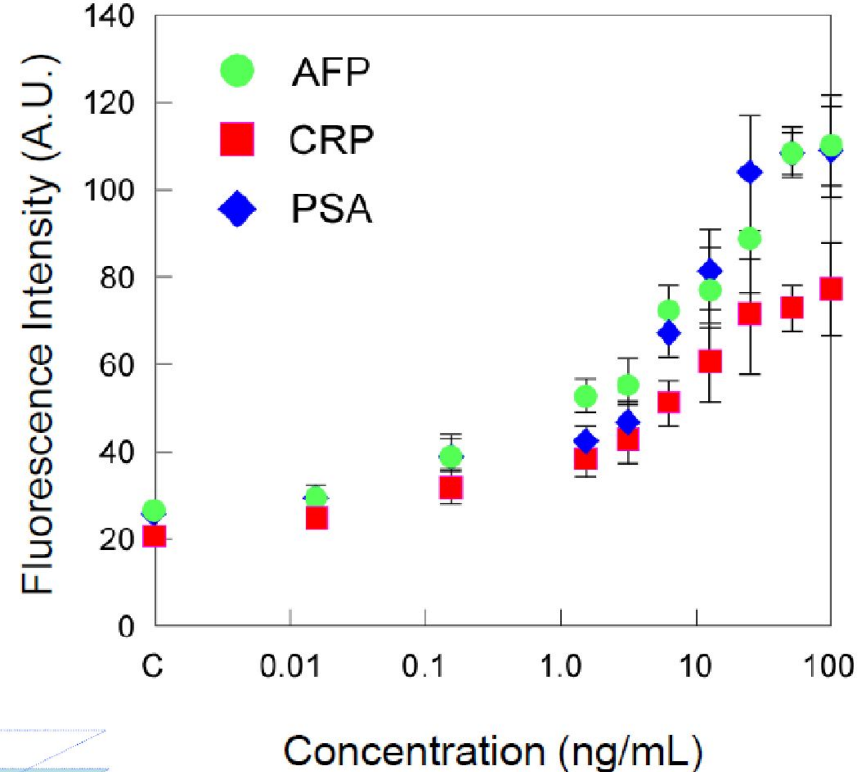
Синтез массивов ДНК DNA synthesis

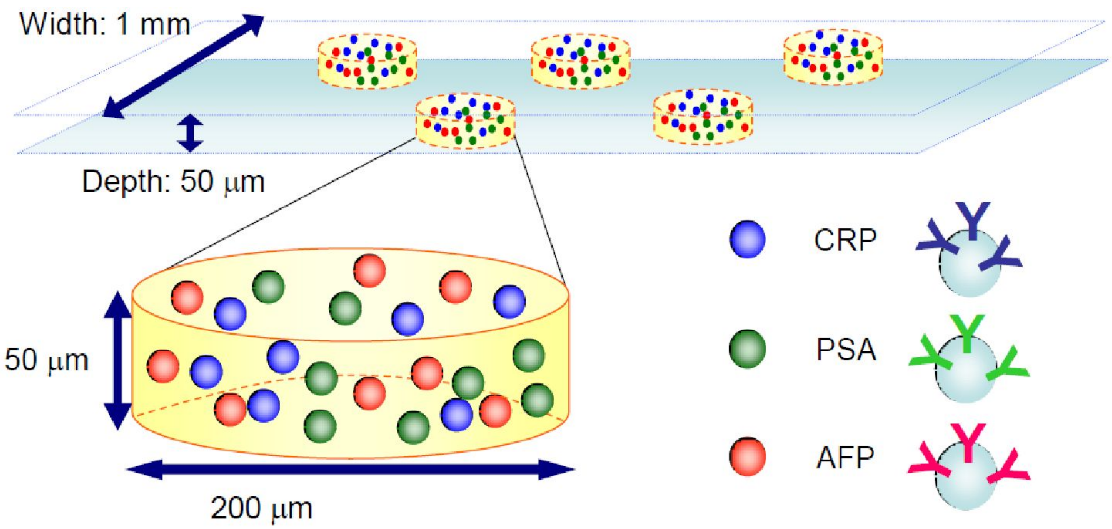


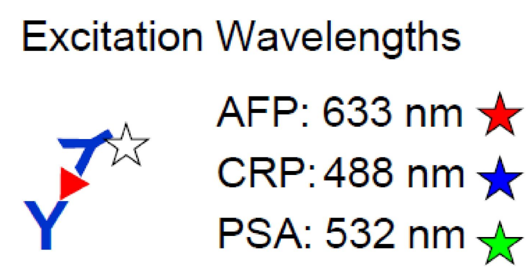
With 25 nucleotides in a sequence, there are 4^{25} (equal to 10^{15}) different combinations that can be made with this process. However, with a final chip size of 1.28 cm^2, there is only enough space for about 320,000 squares with different sequences.

Анализ крови – экспресная диагностика рака Cancer tumor detection



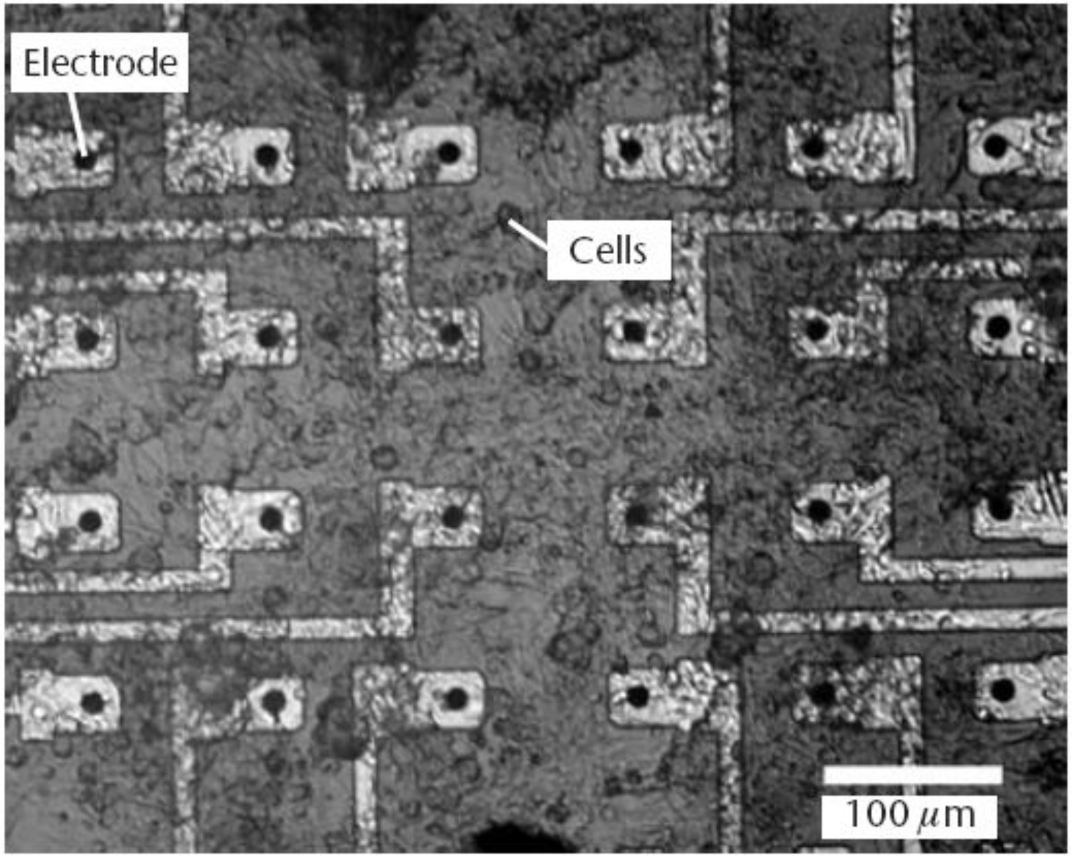






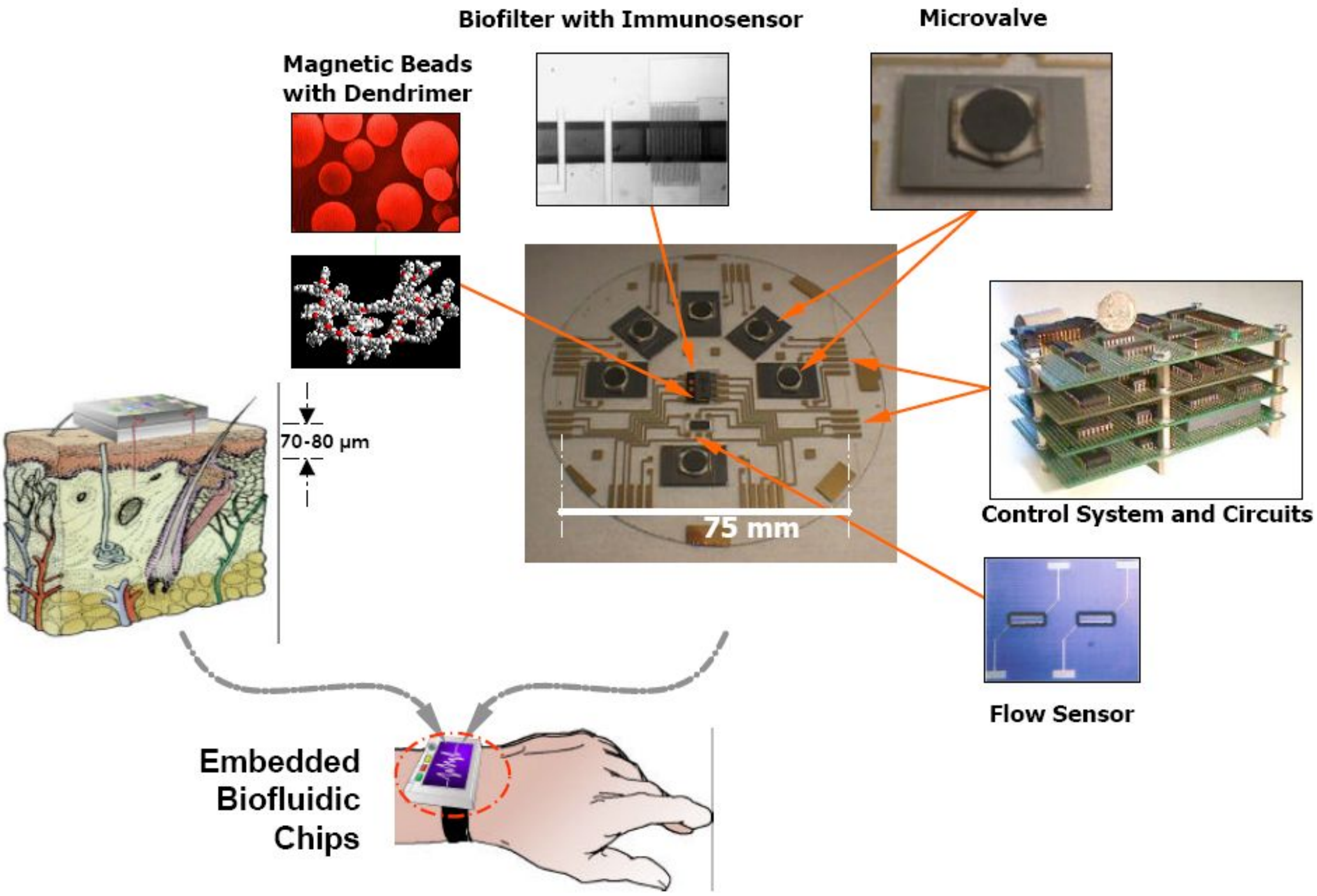
AFP: Tumor marker (Liver cancer)
CRP: Inflammation marker
PSA: Tumor marker (Prostate cancer)

Выращивание и изучение живых клеток
Growth and study of living cells



Photograph of a cultured *syncytium* spontaneously beating over a microelectrode array. The platinum electrodes are 10 μm in diameter with a spacing of 100 μm. The electrodes measure the extracellular currents generated by a traveling wave of action potential across the sheet of living cells. (*Courtesy of:* B. D. DeBusschere of Stanford University, Stanford, California.)

Интегрированная биосистема Integrated biosystem



Рынок НЭМС

Analysis of Worldwide MEMS Markets
(in Millions of U.S. Dollars)

	2002	2007
Microfluidics	1404	2241
Optical MEMS	702	1826
RF MEMS	39	249
Other actuators	117	415
Inertial sensors	819	1826
Pressure sensors	546	913
Other sensors	273	830
Total	3900	8300

Geographical Distribution of the World MEMS Production Facilities

North America	139
Germany	34
France	20
United Kingdom	14
Benelux	17
Scandinavia	20
Switzerland	14
Rest of Europe	10
Japan	41
Rest of Asia	31

In-Stat/MDR, "Got MEMS? Industry Overview and Forecast," Report IN030601EA, 6909 East Greenway Parkway, Suite 250, Scottsdale, AZ 85254,

Yole Developement, "World MEMS Fab," 45 Rue Sainte Genevieve, 69006 Lyon, France

Заключение Conclusion

- МЭМС и НЭМС представляют собой обширное семейство портативных приборов, датчиков и устройств. Wide variety of portable devices.

- Основным материалом НЭМС является кремний. Material of choice for MEMS is Si.

- Технологии НЭМС разработаны на базе технологий полупроводниковой электроники. MEMS technology is taken from electronics

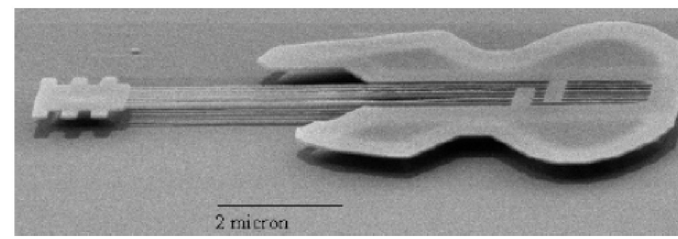
- Уровень технологии НЭМС обеспечивает массовое производство надежных приборов и устройств различного назначения. NEMS technology allows mass production.

- Основными областями применения НЭМС являются биология и медицина, системы безопасности, системы связи и навигации, электроника и фотоника. Major application areas are biology, medicine, safety systems, navigation, communications, electronics, photonics

World smallest car

World's smallest car sitting on a coin. The car is 4.8mm long and runs on a 0.67mm electric motor.

World smallest guitar



A 10 µm long Si guitar (same size as a single cell) with six strings, each ~50 nm (100 atoms) wide. (Cornell University)

Virtual reality system

The end !