# Наномеханика

#### Nanomechanics of materials and systems

Лекции 14 МЭМС и НЭМС: датчики ускорения и поворота, наноприводы, оптические и электронные системы MEMS and NEMS sensors of acceleration and rotation, actuators, optical and electronic systems Базовая структура датчика ускорения Base structure of acceleration sensor



Resonant frequency:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{M}}$$

Noise equivalent acceleration:

$$a_{noise} = \sqrt{\frac{8\pi K_B T f_r B}{Q M}} \ ; \ B < f_r$$

$$K_B$$
 = Boltzmann constant

B = Bandwidth

Q = Quality factor

The basic structure of an accelerometer, consisting of an inertial mass suspended from a spring. The resonant frequency and the noise-equivalent acceleration (due to Brownian noise) are given.

## Пьезорезистивный датчик ускорения **Piezoresistive acceleration sensor** Acceleration Outer frame Base Mass Hinge **Bondpads** {110} plane Lid Boron doped piezoresistor

Illustration of a piezoresistive accelerometer from Endevco Corp., fabricated using anisotropic etching in a {110} wafer. The middle core contains the inertial mass suspended from a hinge. Two piezoresistive sense elements measure the deflection of the mass. The axis of sensitivity is in the plane of the middle core. The outer frame acts as a stop mechanism to prevent excessive accelerations from damaging the part.  $f_r=28$  kHz. The piezoresistors are 0.6 µm thick and 4.2 µm long, aligned along <111> direction for maximum performance. The output in response to an acceleration of 1G is 25mV for a Wheatstone bridge excitation of 10V.

## Емкостной датчик Capacitive sensor



#### Емкостной датчик ускорения. Capacitive accelerometer.



Illustration of a bulk micromachined capacitive accelerometer. The inertial mass in the middle wafer forms the moveable electrode of a variable differential capacitive circuit. Electronic circuits sense changes in capacitance, then convert them into an output voltage between 0 and 5V. The rated bandwidth is up to 400 Hz for the  $\pm 12G$  accelerometer, the cross-axis sensitivity is less than 5% of output, and the shock immunity is 20,000G. Measuring range is from  $\pm 0.5G$  to  $\pm 12G$ . (VTI Technologies of Vantaa, Finland.)

#### Емкостной датчик ускорения – последовательность производства Production of capacitive accelerometer



1. Etch recess cavities in silicon



2. Deposit and pattern three masking layers; anisotropic etch silicon



3. Remove first masking layer; anisotropic etch silicon



4. Remove second masking layer; anisotropic etch silicon

#### Емкостной датчик ускорения. Capacitive accelerometer.



Acceleration rating is from 1G to 100 G, excitation frequency is 1 MHz, C =  $10^{-13}$ F bandwidth is 1-6 kHz, mass is 0.3 - 100 µg, Brownian mechanical noise for 0.3 µg is 225 µG Hz<sup>1/2</sup>

Illustration of the basic structure of the ADXL family of surface micromachined accelerometers. A comb-like structure suspended from springs forms the inertial mass. Displacements of the mass are measured capacitively with respect to two sets of stationary finger-like electrodes. (Analog Devices, Inc., Norwood, Massachusetts, USA.)

Емкостной датчик ускорения, произведенный с помощью DRIE. Capacitive accelerometer using DRIE.



Scanning-electron micrograph of a DRIE accelerometer using 60- $\mu$ m-thick comb structures. (Courtesy of: GE NovaSensor of Fremont, California.) Using structures 50 to 100  $\mu$ m deep, the sensor gains an inertial mass, up to 100  $\mu$ g, and a capacitance, up to 5 pF. The relatively large mass reduces mechanical Brownian noise and increases resolution. The high aspect ratio of the spring practically eliminates the sensitivity to *z*-axis accelerations.

#### Сравнение пьезорезистивного, емкостного и электромагнитного методов измерения Comparison of different sensing

Piezoresistive	Capacitive	Electromagnetic	
Simple fabrication	Simple mechanical structure	Structural complexity varies	
Low cost	Low cost	Complex packaging	
Voltage or current drive	Voltage drive	Current drive	
Simple measurement circuits	Requires electronic circuits	Simple control circuits	
Low-output impedance	Susceptible to EMI	Susceptible to EMI	
High-temperature dependence	Low-temperature dependence	Low temperature dependence	
Small sensitivity	Large dynamic range	Sensitivity ∝ magnetic field	
Insensitive to parasitic resistance	Sensitive to parasitic capacitance	Insensitive to parasitic inductance	
Open loop	Open or closed loop	Open or closed loop	
Medium power consumption	Low power consumption	Medium power consumption	

Элементы HЭMC NEMS elements

- Пассивные Passive
- Датчики Sensors
- Приводы (актуаторы) Actuators

## Термический привод Thermal actuator







$$u_x = \sqrt{(l + \Delta l)^2 - l^2} \approx \sqrt{2l\Delta l}$$

#### Пьезоэлектрический элемент (датчик или привод) Piezoelectric sensor and actuator



## Электростатический нанопривод Electrostatic actuator



(a) An illustration of a parallel-plate electrostatic actuator with an applied voltage V and a spacing x. The attractive force is normal to the plate surfaces. (b) An illustration of an electrostatic comb actuator. The attractive force is in the direction of the interdigitated teeth.

#### Сравнение различных наноприводов Comparison of different nanoactuators

Actuation	Max. Energy	Physical and	Estimated	Approximate
	Density	Material Parameters	Conditions	Order (J/cm³)
Electrostatic	$\frac{1}{2} \varepsilon_0 E^2$	E = electric field	5 V/µm	~ 0.1
		$\varepsilon_0$ = dielectric permittivity		
Thermal	$\frac{1}{2} Y (\alpha \Delta T)^2$	$\alpha$ = coefficient of expansion	$3 \times 10^{-6} / ^{\circ}C$	~ 5
		$\Delta T$ = temperature rise	100°C	
		Y = Young's modulus	100 GPa	
Magnetic	$\frac{1}{2} B^2 / \mu_0$	B = magnetic field	0.1 T	~ 4
		$\mu_0$ = magnetic permeability		
Piezoelectric	$\frac{1}{2} Y (d_{33} E)^2$	E = electric field	30 V/µm	~ 0.2
		Y = Young's modulus	100 GPa	
		$d_{33}$ = piezoelectric constant	$2 \times 10^{-12} \text{ C/N}$	
Shape-memory alloy	_	Critical temperature		~ 10 (from reports
				in literature)

Гироскопы и датчики поворота Gyroscopes and tilt sensors



## Кориолисово ускорение Coriolis acceleration

v<sub>Earth</sub>= 1670 cos(lattitude) km/h



Illustration of the Coriolis acceleration on an object moving with a velocity vector  $\mathbf{v}$  on the surface of Earth from either pole towards the equator. The Coriolis acceleration deflects the object in a counterclockwise manner in the northern hemisphere and a clockwise direction in the southern hemisphere. The vector  $\Omega$  represents the rotation of the planet.

#### Базовый датчик угловой скорости Base angular rate sensor



Illustration of the tuning-fork structure for angular-rate sensing. The Coriolis effect transfers energy from a primary flexural mode to a secondary torsional mode. Coriolis acceleration  $a_c = 2\Omega \times v$ .

## Датчик угловой скорости Angular-rate sensor



Illustration of the angular-rate sensor from Daimler Benz. The structure is a strict implementation of a tuning fork in silicon. A piezoelectric actuator excites the fork into resonance. The Coriolis force results in torsional shear stress in the stem, which is measured by a piezoresistive sense element. The measured frequency of the primary, flexural mode (excitation mode) is 32.2 kHz, whereas the torsional secondary mode (sense mode) is 245 Hz lower.

Датчик угловой скорости Daimler Benz – последовательность производства Angular-rate sensor – fabrication steps



1. Etch cavity in SOI wafers



2. Silicon fusion bonding



 Etch front side; stop on buried oxide



4. Etch oxide



 Define and pattern piezoelectric films and piezoresistors



 Back-side etch; stop on buried oxide; plasma etch release

## Датчик угловой скорости Angular-rate sensor



Illustration of the Delphi Delco angular-rate sensor and the corresponding standing-wave pattern. The basic structure consists of a ring shell suspended from an anchor by support flexures. A total of 32 electrodes (only a few are shown) distributed around the entire perimeter of the ring excite a primary mode of resonance using electrostatic actuation. A second set of distributed electrodes capacitively sense the vibration modes. The angular shift of the standing-wave pattern is a measure of the angular velocity.

## Датчик угловой скорости Angular-rate sensor





1. Deposit and pattern oxide



2. Deposit and pattern metal



3. Resist spin and pattern



4. DRIE



Illustration of the CRS angular-rate sensor from Silicon Sensing Systems (UK&Jp) and corresponding fabrication process. The device uses a vibratory ring shell design, similar to the Delphi Delco sensor. Eight current loops in a magnetic field, *B*, provide the excitation and sense functions. For simplicity, only one of the current loops is shown.

## Микро/наногенераторы: Vibration Harvesting



Illustration of unimorph configuration (left) and SEM of a prototype device (right, courtesy of S.-G. Kim).

> Vibrations generate 10's-100's of µW

Power vs. normalized frequency with varying electrical load resistance

## Self-powered Wireless Corrosion-monitoring System



Wireless sensor system schematics. The selfpowered sensor node transmits data to a receiver at the base station.

#### Оптические переключатели Optical switches



Illustration of a 2 x 2 binary reflective optical switch fabricated using SOI wafers and DRIE. An electrostatic comb actuator controls the position of a micromirror. In the cross state, light from an input fiber is deflected by 90°. In the bar state, the light from that fiber travels unobstructed through the switch. Side schematics illustrate the signal path for each state. The typical response time is 500 µs.

#### Проекционные дисплеи Projectors



Illustration of a single DMD pixel in its resting and actuated states. The basic structure consists of a bottom aluminum layer containing electrodes, a middle aluminum layer containing a yoke suspended by two torsional hinges, and a top reflective aluminum mirror. An applied electrostatic voltage on a bias electrode deflects the yoke and the mirror towards that electrode.

#### Микрозеркала Micromirrors

Each micromirror is 16  $\mu$ m square and is made of aluminum. The pixels are normally arrayed in two dimensions on a pitch of 17  $\mu$ m to form displays with standard resolutions from 800 x 600 pixels (SVGA) up to 1,280x1,024 pixels (SXGA). The fill factor is approximately 90%. The mechanical switching time is 16  $\mu$ s.



Illustration of optical beam steering using the switching of micromirrors. Off-axis illumination reflects into the pupil of the projection lens only when the micromirror is tilted in its +10° state, giving the pixel a bright appearance. In the other two states, the pixel appears dark.

#### Микрозеркало - последовательность производства Micromirror fabrication steps





2. Deposit hinge metal; deposit and pattern oxide hinge mask



5. Deposit spacer 2 and mirror



3. Deposit yoke and pattern yoke oxide mask



Pattern mirror and etch sacrificial spacers

#### Дифракционный оптический переключатель Optical diffraction switch



Unactuated - reflective state

Actuated - diffractive state

Illustration of the operating principle of a single pixel in the GLV. Electrostatic pull down of alternate ribbons changes the optical properties of the surface from reflective to diffractive.

## Цветной проекционный элемент Color projection



Implementation of color in a GLV pixel. The pitch of each color subpixel is tailored to steer the corresponding light to the projection lens. The aperture blocks the reflected light but allows the first diffraction order to enter the imaging optics. The size of the pixel is exaggerated for illustration purposes. Switching speed is about 20 ns.

## Перестраиваемый лазер Tunable laser



Illustration of the building blocks of a laser. A gain medium amplifies light as it oscillates inside a resonant cavity. Only select wavelengths called longitudinal cavity modes that are separated by a frequency equal to *c*/2*L* may exist within the cavity. A wavelength filter with a narrow transmission function selects one lasing mode and ensures that the output light is monochromatic.

#### Внешний резонатор для перестраиваемого лазера External resonator for a tunable laser



(a) Illustration of the Littman-Metcalf external cavity laser configuration. Light from the laser diode is collimated and diffracted by a grating acting as a wavelength filter. Lasing occurs only at one wavelength, whose diffraction order is reflected by the mirror back into the cavity. (b) Rotating the mirror around a virtual pivot point changes the wavelength and tunes the laser.

#### Массив лазеров и оптоволокно Collimation of a laser from array into an optical fiber



Fiber

Schematic illustration of the tunable array of DFB lasers from Santur Corporation of Fremont, California. Once a DFB laser in the array is electrically selected, a micromirror steers its output light through a focusing lens into an optical fiber. Changing the temperature of the DFB laser array using a TEC device tunes the wavelength over a narrow range. The illustration on thefar left depicts the simplified internal structure of a single DFB laser. Both facets of the semiconductor diode are coated with an antireflection (AR) coating.

## Микрозеркало Micromirror



Schematic cross section of the micromirror used within the tunable laser from Santur Corporation. The device consists of a double-gimbaled mirror structure supported by torsional hinges. A gold layer defines the high-reflectivity mirror surface that remains at ground potential. Four gold electrodes on an anodically bonded glass substrate actuate the mirror and cause rotation around the hinges.

#### Многоканальный оптический переключатель Multichannel optical switch





Schematic illustration of the 3-D architecture for an  $N \times N$ switch or photonic cross connect. A beam-steering micromirror on a first plate points the light from a collimated input fiber to another similar micromirror on a second plate, which in turn points it to a collimated output fiber. This system architecture requires a total of 2N continuously tilting mirrors in two directions. To minimize the maximum N output fibers angular displacement of the mirrors, the two plates are positioned at 45° relative to the incident light.

#### Замещение пассивных электронных элементов Replacement of passive electronic components



improved performance

## Индуктивность Microinductor



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 HЭМС Fabrication of microinductor



3. Strip photoresist. Electroplate Au/MoCr/Au with copper.

## Переменная емкость Tunable capacitor



#### Резонатор Resonator



Illustration of a micromachined folded-beam comb-drive resonator. The left comb drive actuates the device at a variable frequency  $\omega$ . 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



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



#### MicroAssembly Technologies of Richmond, California, USA

# To be continued

## Домашнее задание

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