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From MEMS to NEMS

1.1. Micro- and nanoelectromechanical systems: an overview

This chapter will begin with a definition of nanoelectromechanical systems (NEMS), based on microelectromechanical systems (MEMS): at least two of the latter's three geometric dimensions were drastically reduced to nanometric size. Microsystems are miniature electromechanical transducer components used in actuators or sensors [BUS 98, MAD 11]. They contain a mechanical element that can move (Figure 1.1) under the action of a force. This force can be caused by the physical stimulus to be measured, such as pressure difference (Figure 1.2) or acceleration (Figure 1.3). The actuation force can also be artificially induced when the mobile body needs to be placed in controlled movement. In Figure 1.4, a membrane is actuated by an electrostatic force and constitutes a radio frequency (RF) microswitch. Figure 1.5 presents the different types of MEMS such as an optical micromirror, a microcantilever (microbeam) and a vibrating plate, which can be used as an RF clock.

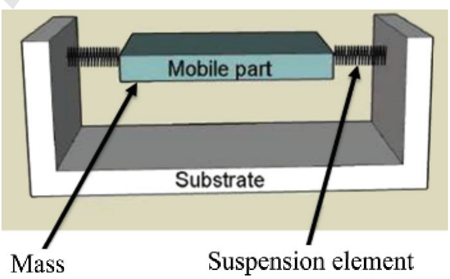

Figure 1.1. *Representation of a suspended mechanical structure containing a mass attached to the support by two suspensions enabling it to move (laterally and/or horizontally)*

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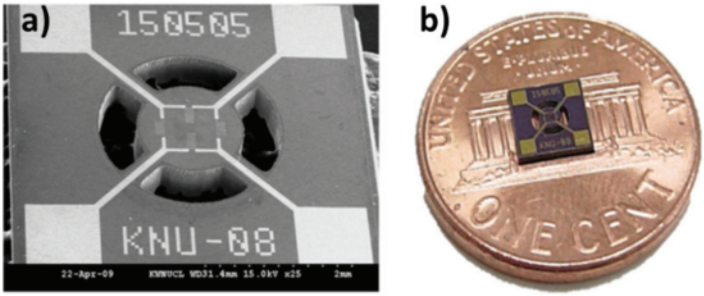

Figure 1.2. *Microsystem with a suspended membrane whose movement is caused by the force to be measured: a) micro pressure sensor (vertical movement of the membrane as a result of a pressure gradient); b) size of this component compared with a one cent coin [KIM 12]*

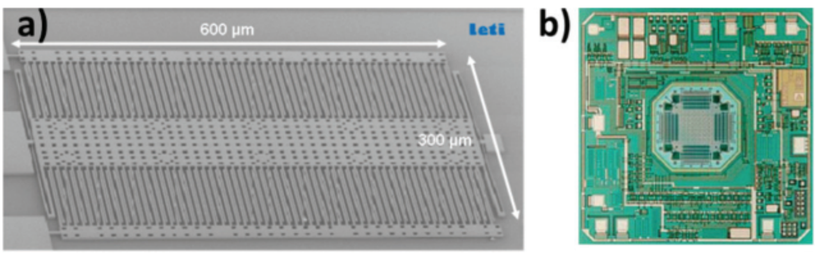

Figure 1.3. *a) Microaccelerometer with capacitive detector via interdigitated electrostatic combs (horizontal movement of the test mass subjected to acceleration) (source: LETI); b) example of an integrated circuit serving this sensor (source: ST Microelectronics)*

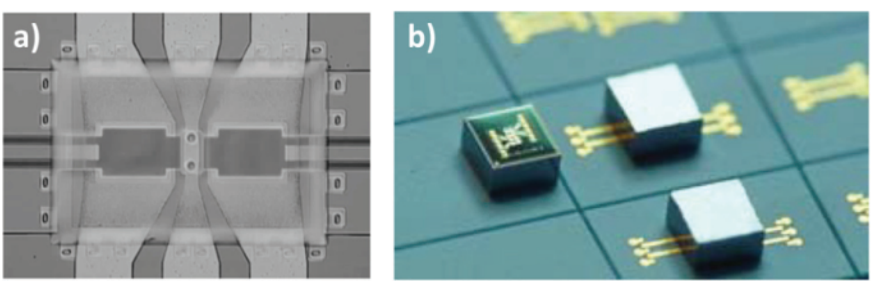

Figure 1.4. *a) RF microswitch: membrane actuated vertically by an electrostatic force enabling or not enabling ohmic contact between the two tracks depending on its position (source: LETI); b) the packaging of this component and the component on a circuit*

In development since the 1970s, MEMS have been used in aeronautics [BAR 11], automobiles and consumer applications since the 1990s. For instance, inertial sensors such as microaccelerometers (see Figure 1.3), gyrometers or magnetometers have been integrated on a large scale into cars (acceleration sensor for the release of the airbag), games consoles (Wii) and even mobile phones [YAZ 98, BEL 05]. Microactuators are used in video-projectors, microphones or to constitute micropumps for medical fluidic applications [THI 00]. More recently, MEMS have started to be integrated into RF circuits as switches (Figure 1.4) or reference clocks (Figure 1.5) [NGU 00]. MEMS have now reached a sufficient level of maturity such as to leave the field of pure research and are currently being developed directly in research and development (R&D) by big industrial players such as Bosch and ST Microelectronics [YOL 12].

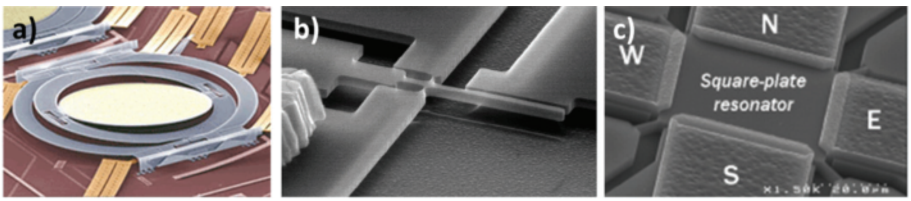

Figure 1.5. *a) Analog devices two axes micromirror: the plate can move around two axes. These torsional movements are caused by an electrostatic moment [AKS 03]; b) a cantilever actuated horizontally by an electrostatic force between the beam and the control electrode [MIL 10]; c) square vibrating membrane forming an RF oscillator actuated by capacitive force [ARC 10]*

NEMS appeared in the early 2000s. Unlike MEMS, NEMS are an emerging technology. NEMS have long been tools devoted to fundamental studies to probe mesoscopic physical mechanisms. Their extremely small size makes them extremely sensitive to any external stimulus. To demonstrate this, Figure 1.6 shows the typical size of several mechanical structures making the move from microaccelerometers – as present in car airbags – to suspended silicon nanowires whose electrical and thermal conducting properties are profoundly modified by the effect of size.

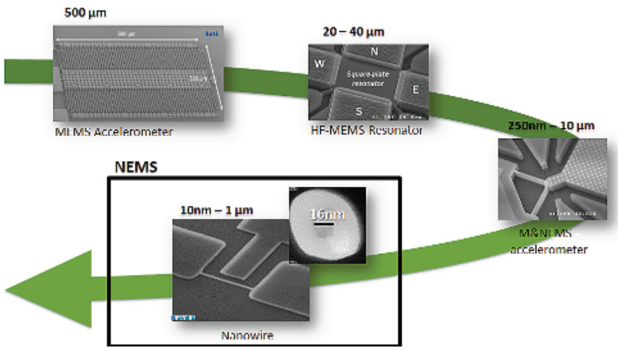

Figure 1.6. *From MEMS to NEMS: typical sizes*

Their extreme sensitivity opens the way to entire sectors of applications in biochemical analyses, which were not addressed by their big brothers, MEMS [EOM 11], such as force sensors [ARL 06, RUG 04] and ultra-sensitive mass sensors [EKI 04a, YAN 06, CHA 12] (shown in Figure 1.7). The principle of measuring mass landing on the surface of NEMS is relatively simple: it consists of monitoring the frequency shift of a NEMS kept at vibration (at a fixed controlled amplitude) using a closed loop circuit via a "Phase Locked Loop" (PLL) or an auto-oscillating circuit. Any element left on the surface of the nanosensor induces a frequency change, which we measure continuously (the mass and/or surface constraints change). This is known as a gravimetric effect (see Figure 1.8). Naturally, this detection principle can be combined with one or more principles, such as the variation of the conductance of NEMS caused by a variation of the electrostatic surface potential to potentially increase the number of measuring parameters and thereby precision. Pushing this approach forward, NEMS may be used as core components of a future mass spectrometer for proteomic analyses on a cell by cell basis [NAI 09, HAN 12]. In the short-term, NEMS will probably be used as sensors in multi-gas analysis systems. Details about these two applications will be provided in Chapter 5. Over time, this technology will be able to quantify gases that are potentially dangerous such as volatile organic compounds (VOCs) to analyze indoor air quality and even identify biomarkers in breath [ARC 1, BAR 12a, FAN 11]. "NEMS" technology can also be used to constitute new probes for near-field tools (magnetic resonance force microscopy and atomic force microscopy) [MID 00].

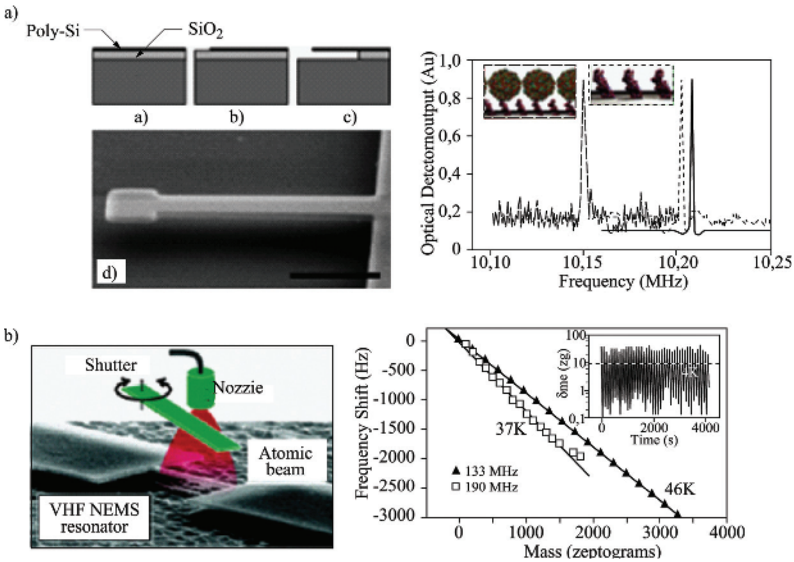

Figure 1.7. *Example of mass measurement: a) Baculovirus measurements according to Ilic et al. [ILI 04]; b) xenon atom measurements according to Yang et al. [YAN 06] (the noise floor is 7 zg or 30 xenon atoms). For a color version of the figure, see www.iste.co.uk/duraffourg/nems.zip*

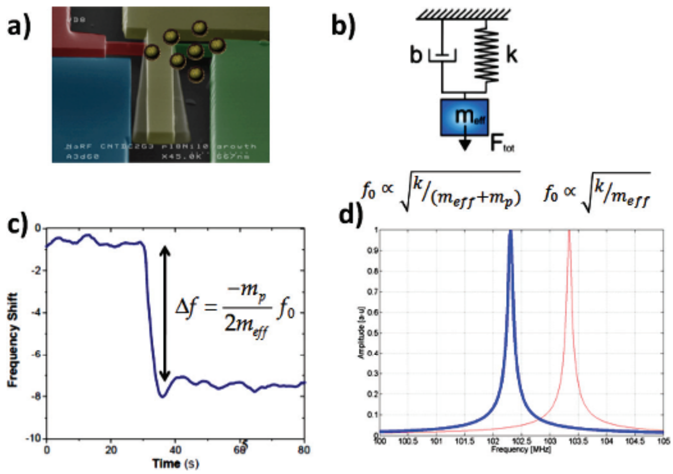

Figure 1.8. *The principle of mass measurement: a) example of a nanoresonator on which particles are left (nanocantilever); b) equivalent 1D model of a mass/spring-type resonator; c) shift in frequency caused by the arrival of a particle. The frequency jump allows us to deduce the accreted mass. Running the frequency brings the frequency back up to what is left on the mass; d) from the spectral perspective: shift in the spectrum toward low frequencies*

Mechanical nanostructures have by and large moved beyond the applicative field of sensors and can be used as switches/nanorelays in microelectronics. More specifically, nanoswitches feeding low circuit consumption (or power gating) can be realized. Purely mechanical components have little or no leakage in comparison with classic metal-oxide semiconductor field-effect transistor (MOSFET)-transistors. They can also replace metal-oxide semiconductor (MOS) transistors in direct current (DC/DC) converters, enabling the energy available from a given source to be transposed into a useable form from its charge (the transposition takes place by grinding the energy of the source with the switches). In addition to the replacement of MOS transistors in the aforementioned applications, some researchers have imagined reaching a mechanical memory similar to that of Charles Babbage's 19th Century mechanical calculator. As a result, a great number of works on nanorelays based on mechanical elements, as shown in Figure 1.9, or on NEMS/transistor hybrid elements, displayed in Figure 1.10, have been presented in recent years [LOH 12, GRO 08a, GRO 08b, AKA 09, ABE 06]. While the classic transistor is limited by a slope below the threshold of 60 mV/decade, suspended gate transistors have demonstrated subthreshold slopes of 2 mV/decade, thereby enabling static leakage to be limited [ABE 06].

Chapter 2 of this book will explore the most important transduction principles (actuation and detection) used on this scale.

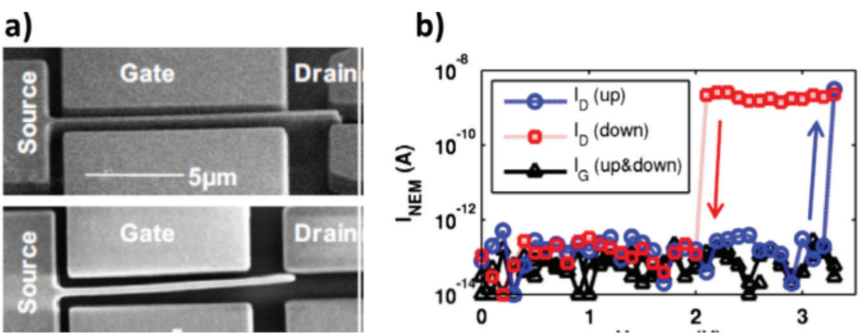

Figure 1.9. *Example of a nanorelay realized with a suspended nanocantilever [CHO 09]: a) the nanorelay seen through a scanning electron microscopy (SEM); b) example of current measurement: ON state when the beam is stuck to the drain electrode, OFF state without current when the beam is relaxing. Leakage is 5 × 10^{-14} A at the OFF state, which is several orders of magnitude lower than in current MOSFET transistors. For a color version of the figure, see www.iste.co.uk/duraffourg/nems.zip*

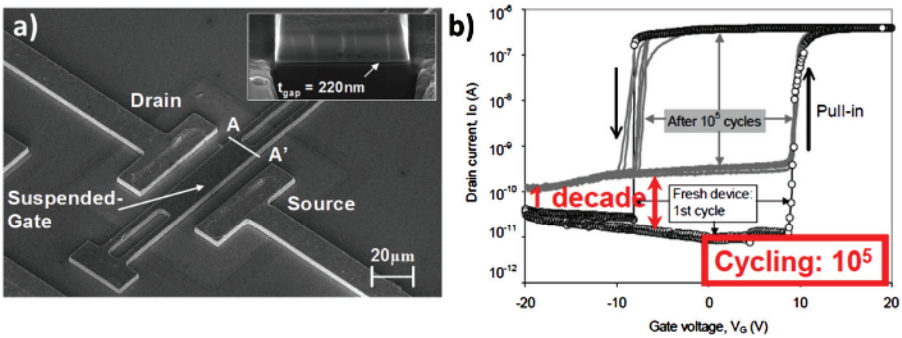

Figure 1.10. *Suspended gate MOSFET (SG-MOSFET): a) a beam acts as a suspended gate positioned above an MOS transistor channel; b) the current is modulated according to the position of this gate – in high position, the transistor is switched off and in low position (the gate is stuck to the channel) the transistor is on. Leakage is 10^{-11}A then 10^{-10} after 10^5 cycles*

NEMS are also very good tools for observing mesoscopic phenomena [BLE 04]. A large number of teams are specifically looking to measure the final displacement of a vibrating nanobeam at the quantum limit [SCH 05]. This limit corresponds to the fundamental vibrational quantum state of NEMS. A beam kept at high frequency oscillation ω_0 and at low temperature ($\hbar\omega > k_B T$) is a quantum oscillator and can thus be described by the formalism of quantum physics (Euler–Bernouilli's classic mechanical equation will be quantified). Heisenberg's uncertainty principle predicts that the position of a beam cannot be known with greater precision than $\Delta x_{SQL} = \sqrt{\hbar / 2m\omega_0}$ where m is the actual mass of the beam and ω_0 is its resonance eigen-frequency [BRA 92]; Δx_{SQL} is called the standard quantum limit. In other words, the measurement disrupts the state of the system we are looking to measure. Two problems arise when we seek to reach this fundamental limit. It is necessary to cool the system such as to reach the quantum regime. Typically for a resonator with a frequency of 1 GHz, the temperature must be lower than 50 mK. This temperature cannot be reached using classic cryogenic means. An ultra-low noise detection scheme must be used and perturbation of the quantum state of the system must be kept to a minimum. The measurement system has a back-action effect on the quantum nanosystem and vice versa. This effect tends to modify the resonance frequency of the quantum nanoresonator, its local temperature and finally its amplitude via the modification of the damping. This permanent interaction between the detector and the quantum system (the cooled NEMS) sets the detection limit just slightly above the standard quantum limit [CAV 82]. It is also possible to use back-action to locally cool the NEMS below the cryogenic room temperature in order to reach the fundamental state.

The displacement of the quantum resonator can be measured by realizing a capacitive coupling between the nanoresonator and a mesoscopic system such as a single-electron transistor (SET) [KNO 03, LAH 04, NAI 06] (see Figure 1.11), a quantum box or quantum points of contact [CLE 02a]. The beam constitutes an electrostatic gate controlling the electrons leaping from one point to another. Another method consists of using superconducting quantum interference device (SQUID) micromagnetometers, one branch of which is constituted by the vibrating beam [ETA 08, BLE 08, POO 11].

Physicists have also been inspired by work on cooling atoms that exchange their energy through an anti-Stokes interaction with photons of laser sources [COH 98] to both reach the fundamental state of the resonator[1] and read its movement. The mechanical system is, therefore, coupled with an optical resonant cavity with an extremely high level of fineness. According to an early measurement diagram, the microsystem is replaced with one of the mirrors of a Fabry–Pérot cavity or is included in the optical cavity. The measurement is, therefore, interferometric and the optomechanical interaction is realized via the pressure force exerted by the photons over the mechanical element [SCH 06, KIP 08, GRÖ 09, MAH 12, GIG 06]. In the second approach, the mechanical system interacts via the evanescent coupling with integrated optical microresonators such as rings or photonic crystals [ANE 09, SCH 08, SCH 09, LIN 09, LIN 10]. Similarly, the nanoresonator can be coupled with a microwave resonant cavity [NAI 06, O'CO 10, HER 09]. These optomechanical systems will be presented in Chapter 4.

Mesoscopic physics has also been applied to the domain of quantum information using Cooper-pair boxes [NAK 99, VIO 02] or micro-SQUIDs [SCH 00a]. For the former, the qubit is constituted of the superposition of quantum states of excess charge in a superconducting island (coupling is electrostatic), whereas for the latter, the qubit arises from the superposition of states of flow (coupling is magnetic). Recently, the team of K. Schwab

1 Back-action cooling of the light on the resonator.

coupled a Cooper-pair box with a nanoresonator to read quantum states of charge [LAH 09]. For a complete description of superconducting qubits and their application in quantum calculus, please refer to [BLA 03]. In the same vein, nanomechanical structures have been put in oscillation via a smart transduction based on the charge shuttle [GOR 98, ERB 01]. Different experimental attempts to measure the quantum heat brought by a phonon have also been conducted [SCH 00b, FON 02].

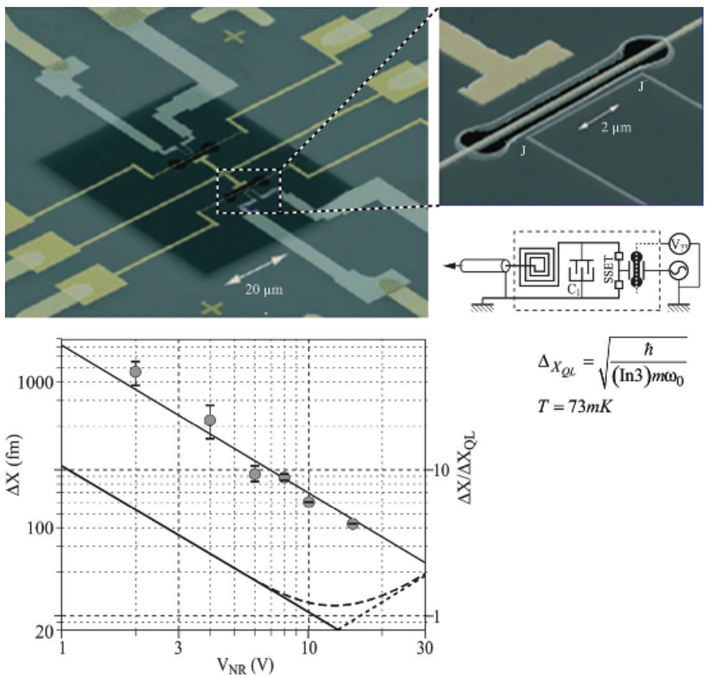

Figure 1.11. *Final measurement at low temperature of the displacement of an oscillating beam at 20 MHz according to Lah et al. [LAH 04] – a SET is used as an electrometer with a sensitivity of ~10 µe/√Hz – black curve: the sound of gunfire – red curve: the sound of the counter reaction – blue curve: the square sum considering uncorrelated sources of noise. For a color version of the figure, see www.iste.co.uk/duraffourg/nems.zip*

1.2. Conclusion

NEMS are interesting both in terms of fundamentals and applications. They often have high mechanical resonance frequencies (typically from 1 to 100 MHz) and dissipate low quantities of energy (mechanical and electrical).

They are sensitive enough to enable mass measurements to be realized at the single molecular level (molecule counting), to count electrons or phonons one by one, or to measure forces approaching the pico-Newton. This statement can be backed up by writing the expressions of the main mechanical properties of a nanobeam dependent on a reduction coefficient α applied similarly to its three dimensions. The expressions and the typical values of these mechanical parameters are summarized in Table 1.1. It can be seen that reducing the scale results in a linear increase in the resonance frequency when α decreases. The mechanical and thermal time constants decrease depending on the scale factor according to the linear and square laws. In other words, NEMS respond to requests as fast as the size of the nanobeam is small. A nanowire 1 µm long for a 50 nm^2 section in silicon can, therefore, thermalize in less than 10 ns. It is, therefore, possible to actuate high frequency NEMS with a thermomechanical force, something that was not possible with microsystems. This also means that a NEMS sensor can be used to detect fast phenomena (~1 µs or less)[2].

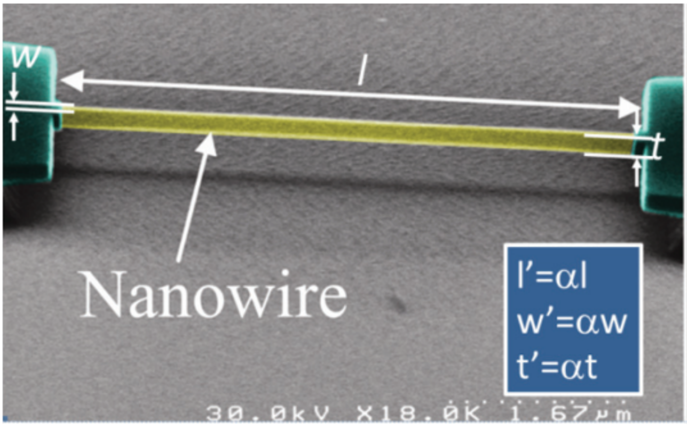

Figure 1.12. *Suspended silicon nanowire with a length l of (3 µm), a width w of (80 nm) and a thickness t of (160 nm) (source: LETI)*

2 The overall response time of the sensor must, however, take monitoring electronics (actuation and detection) into consideration. In some cases, this part will be slower than the NEMS itself.

Parameters	Law		Typical values
Mass	$m \propto wlt$	α^3	1 pg–10 fg
Stiffness	$k \propto Ewt^3/l^3$	α	1 N/m–10^2 N/m
Frequency	$f \propto \sqrt{E/\rho}\, t/l^2$	α^{-1}	10 MHz–1 GHz
Dissipated mechanical energy	$P_{th} \propto 2k_B TQ/\pi f$	α	100 aW–10 fW
Mechanical time constant	$\tau_m \propto Q/2\pi f$	α	0.1–10 µs
Thermal time constant	$\tau_{th} \propto c\rho l^2/\kappa$	α^2	0.1–100 ns
Noise amplitude	$\sqrt{2k_B TQ/fk}$	1	1–100 fm
Noise in force	$\sqrt{2k_B Tk/fQ}$	α	10 fN–1 pN
Mass detection limit	$\delta m = 2m\, \delta f/f_0$	α^3	(ag – yg)

Table 1.1. *Orders of magnitude of the main electromechanical characteristics of a nanowire and the associated scaling laws when a reduction coefficient α is applied to its length, width and thickness: $l'=\alpha l$, $w'=\alpha w$, $t'=\alpha t$ (Figure 1.12) – E, ρ, c, κ are the Young's modulus, density, the thermal capacity and thermal conductivity of the nanowire, respectively. k_B and T are the Boltzmann constant and temperature, respectively*