X-ray pushing of a mechanical microswing

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Abstract

We report here for the first time the combination of x-ray synchrotron light and a micro-electro-mechanical system (MEMS). We show how it is possible to modulate in real time a MEMS mass distribution to induce a nanometric and tunable mechanical oscillation. The quantitative experimental demonstration we present here uses periodic thermal dilatation of a Ge microcrystal attached to a Si microlever, induced by controlled absorption of an intensity modulated x-ray microbeam. The mechanism proposed can be envisaged either for the detection of small heat flux or for the actuation of a mechanical system.

(Some figures in this article are in colour only in the electronic version)

Nanoelectromechanical systems (NEMS) are among the best candidates to measure interactions and accelerations at the nanoscale [1–6], especially when resonating oscillators are used with high quality factor [7–9]. Indeed NEMS and MEMS have been used for the detection of the mechanical effects of light and radiation pressure [10] and thermal switching effects in a lever [11] have been shown as actuation mechanisms for mechanical systems. We show here, for the first time, the interaction between a mechanical system and x-rays. To demonstrate this interaction efficiency we show how mechanical nanodisplacements of a MEMS are triggered using modulated x-ray microbeams. The MEMS is a microswing constituted by a Ge microcrystal attached to a Si microcantilever. The interaction is mediated by Ge absorption of the intensity modulated x-ray microbeam impinging on the microcrystal. We show then that radiation pressure or thermal-strain-induced effects are not effective enough to induce the observed oscillation amplitude in our experiments. The measured oscillation amplitudes can be understood by the changes of the mass distribution at the nanoscale induced by controlled thermal dilation. The small but finite thermal expansion of the Ge microcrystal is large enough to force a nanodisplacement of the Ge microcrystal’s center of mass (COM). This mechanism is based on the small temperature variation induced by a local heating absorption (20 K mW\(^{-1}\)) and, as a consequence, this strategy can be used as a local thermal flux sensor. Moreover this mechanism represents a new actuation scheme for NEMS and MEMS and we show how this effect can be potentially scaled down to offer an actuation mechanism on the nanoscale.

The experimental set-up is presented in figure 1. The microswing position is measured through the interference between the light reflected from the back of the lever and from a cleaved fiber end. This experimental set-up has been shown to produce a sub-Ångström precision in position measurements [5, 6, 11]. SEM images of the microswings used are shown in figures 1(b) and (c). The first Ge microcrystal in figure 1(b) has been directly cut from a Ge wafer by a focused ion beam (FIB). In order to fabricate the micro-oscillator, a cubic-like germanium crystal has been etched from a germanium wafer using the FIB Strata400 from FEI. The cube was welded to the cantilever, in a symmetrical position, using localized FIB deposition of metal. The cubic Ge crystal is 43 μm thick. The lever is a standard silicon AFM cantilever whose dimensions are 350 × 35 × 2 μm\(^3\). This lever has no metallic coating. The second Ge microcrystal is about 23 μm thick (figure 1(c)). It has been manually glued on the side of the cantilever in a very asymmetrical position. For asymmetrically mounted crystals, two types of levers have been used: one bare and another with a metallic coating.
The experiments were performed at the European Synchrotron Radiation Facility (ESRF). The beamlines involved were the anomalous scattering beamline (ID01) and surface science x-ray diffraction (SXRD) beamline (ID03). In ID01 the radiation from the undulators can be tuned from 2.5 to 40 keV with a Si(111) double-crystal monochromator. Focusing is achieved by using beryllium compound refractive lenses (CRLs) \[12\]. The effective focus size is \(\approx 4 \times 6 \, \mu\text{m}^2\) with \(\approx 10^{10} \, \text{photons s}^{-1}\) on the focal spot. At the SXRD beamline the photons were tuned at the Ge K edge using a liquid-nitrogen-cooled monolithic double-crystal Si(111) monochromator. The beam was focused on the sample by a Kirkpatrick–Baez (KB) mirror system located 43 m from the photon source. The beam size at the sample, 1 m from the KB system, is \(\approx 3 \times 5 \, \mu\text{m}^2\) with \(\approx 10^{12} \, \text{photons s}^{-1}\) on the focal spot.

Figure 2 presents the mechanical response measured around the first resonance frequency \(\omega_0\) for different geometries and experimental set-ups. In table 1 a comparison between the simulated resonant frequency values and the measured ones is presented. The calculated values are obtained using the hypothesis of a simple 1D harmonic oscillator.

In figure 2 the intensity of the x-ray beam impacting on the Ge crystal is modulated at a frequency \(\omega\) sweeping through the lever resonant frequency \(\omega_0\). For x-ray energies below the absorption edge, the lever is already forced to oscillate with amplitudes larger than the thermally induced noise. For energies above the absorption edge we observe an increase of oscillation amplitude for all geometries. The amount of this increase as a function of geometry, microswing characteristic and the position of the Ge microcrystal is the basis of our findings.

Figure 3 reports the mechanical response of the cantilever at resonance, when the x-ray energy is scanned through the germanium K-edge energy. The mechanical response of the microswing matches well the XAS reference spectrum of germanium \[13\]. The two curves have been normalized below the edge and in the continuum atomic part above the edge.

### Table 1. Comparison between the calculated resonant frequency and the measured value for the resonant peaks presented in figure 2.

| Mechanical system | Simulated resonant frequency (Hz) | Measured resonant frequency (Hz) |
|-------------------|----------------------------------|----------------------------------|
| \(2\) (a)         | 2110                             | 2140                             |
| \(2\) (b)         | 3560                             | 3750                             |
| \(2\) (c)–(d))    | 1410                             | 1270                             |

Figure 1. (a) Experimental set-up. The small cylinder (blue ray) is the x-ray beam on the Ge microcrystal at the Si lever end. The big (gray) cylinder represents the optical fiber and the inner (red) ray is the laser beam used to detect the lever position with sub-Ångström precision. ((b) and (c)) SEM images of the Ge cubes glued on the Si lever. In (b) the cut and soldered Ge crystal, using a focused ion beam, has been positioned at the end of the lever in a symmetrical position. In (c) a Ge crystal has been manually glued on the side in a very asymmetrical position.

Figure 2. Measured resonance curve of the first oscillating mode for all levers. In gray (red) the x-ray beam energy is set below the K1s edge \((E_{\text{ph}} = 11.07 \, \text{keV})\), while in black it is set at the K1s edge \((E_{\text{ph}} = 11.103 \, \text{keV})\). (a) Uncoated cantilever \((k = 0.025 \, \text{N m}^{-1}, Q = 86, I_0 = 7.4 \times 10^{10} \, \text{ph s}^{-1})\) with Ge block glued on the side and x-ray beam parallel to the oscillation direction. (b) Coated cantilever \((k = 0.027 \, \text{N m}^{-1}, Q = 60, I_0 = 3.5 \times 10^{10} \, \text{ph s}^{-1})\) with Ge block glued on the side and x-ray beam parallel to the oscillation direction. (c) Uncoated cantilever \((k = 0.135 \, \text{N m}^{-1}, Q = 75, I_0 = 2.4 \times 10^{12} \, \text{ph s}^{-1})\) with Ge block glued below and x-ray beam parallel to the oscillation direction. (d) Same as in (c) with x-ray beam perpendicular to the oscillation direction.
the absorbed photon flux \( I_h \) oscillations after the K edge with respect to the reference Auger electrons. Absorbed photons generate fluorescence, Coster–Kronig and their cascades. At energies higher than the Ge K edge the mean free path (a few nanometers) of the Auger electrons and photons then contribute to the heating because of the short energy.

The decreased amplitude of the XAFS peak and oscillations after the K edge with respect to the reference spectra are due to this intrinsic self-absorption effect. In table 2 the absorbed photon flux \( I_h \) is calculated for two lever/crystal configurations, for two x-ray beam directions, and for coated and uncoated levers. The ratio of the measured oscillation amplitudes \( x(\omega_0) \) above and below the K-edge energy is consistent with the ratio of absorbed photons. The temperature increase \( \Delta T \) can be calculated taking into account the overall energy deposited in the crystal and the heat flow through the lever (cooling by radiation and convection is negligible here). The absorbed power \( W \) is then

\[
W = C \dot{T}(t) + G(T(t) - T_0)
\]

\[
T(t) = T_0 + \frac{W}{G} \left(1 - e^{-\frac{t}{\tau}}\right)
\]

where \( T_0 \) is the ambient temperature and \( T(t) \) the block temperature as a function of time. \( \Delta T(\omega) \) is then

\[
\Delta T(\omega) = \frac{W}{G} \frac{1}{1 + \omega \tau}
\]

\[
\tau = \frac{C}{G}
\]

\( \omega \) is the beam chopper frequency and \( \tau \) is the ratio between the thermal capacity of the Ge block and the thermal conductivity of the Si lever. For the uncoated and coated levers of figures 2(a) and (b) the experimental conditions are nearly identical whereas the oscillation amplitude is 10 times larger in 2(a) than in 2(b). This difference can be described using those last equations. The presence of the metallic coating increases the thermal conductivity \( G \) of the system and therefore induces a consequent decrease of \( \Delta T \) compared to the uncoated lever.

However, this description cannot explain the difference of the amplitude of oscillation between figures 2(a) and (c). The oscillation amplitude in figure 2(c) is 3 times larger than in 2(c) against a photon flux 40 times bigger and an absorption rate 25% higher because of the difference in Ge crystal dimensions. The difference in the mechanical properties of the cantilever (2(a) \( k = 0.025 \text{ N m}^{-1} \), 2(c) \( k = 0.135 \text{ N m}^{-1} \)) cannot explain such a large discrepancy. However, the position of the Ge crystal and this symmetry with respect to the lever has not been considered. This remark is essential to the conclusion of this paper. We show that the thermally induced change in the distance between the Ge crystal COM and the lever axis controls the system dynamics.

The thermally induced change in the COM position is determined by

\[
\Delta l(\omega) = l_0 \alpha \Delta T(\omega)
\]

where \( l_0 \) is the distance between the block COM and the lever axis and \( \alpha \) the linear thermal expansion coefficient.

For a simple 1D mechanical oscillator the oscillation amplitude is given by

\[
x(\omega) = \frac{x_1(\omega) \sqrt{\psi(\omega)}}{Q^2 + \omega^2}\left(\frac{Q^2}{Q^2 + \omega_0^2} + \omega_0^2\right)
\]

where \( \psi(\omega) \) is the oscillator transfer function. Here, \( x_1(\omega) \) corresponds to \( \Delta l(\omega) \).

Considering the MEMS as the whole system constituted by the cantilever and the Ge microcrystal, the induced increase in the Ge crystal size can be read as an induced change in the mass distribution of the mechanical system.
resonance of $1$ with the measured quality factor of $86$ and the amplitude at

correspondence for a coated and an uncoated lever with an asymmetrical geometry like in figure 1(c). The x-ray beam is here parallel to the
direction of oscillation. The second part presents the comparison for an uncoated lever with a symmetric geometry. The x-ray beam is here either parallel or perpendicular to the direction of oscillation.

| $E_{ph}$ | $T_{Ge}$ | $u_{Ge}$ | $T_{OGe}$ | $l_0$ | $x(\omega_0)$ (nm) |
|---------|---------|---------|---------|------|------------------|
| 11.07   | 0.72    | 0       |         | 0.28 $l_0$ | 1.053            |
| 11.103  | 0.083   | 0.535   | 0.83    | 0.51 $l_0$ | 1.902            |
|          |         |         |         | Ratio   | 1.82             |

| $E_{ph}$ | $T_{Ge}$ | $u_{Ge}$ | $T_{OGe}$ | $l_0$ | $x(\omega_0)$ (nm) |
|---------|---------|---------|---------|------|------------------|
| 11.07   | 0.54    | 0       |         | 0.47 $l_0$ | 4.066            |
| 11.103  | 0.009   | 0.535   | 0.33    | 0.63 $l_0$ | 5.898            |
|          |         |         |         | Ratio   | 1.34             |

Figure 4. Schema of the actuation mechanism. In (a) is presented a very asymmetric configuration and in (b) a symmetric geometry. The dotted squares represent the Ge crystal thermal expansion and the black arrows indicate the direction of the effective displacement of the Ge crystal COM.

In the hypothesis of uniform temperature in the Ge block the displacement of the COM with respect to the lever axis is easily calculated using equation (6). As is described in figure 4, when the Ge cube is glued on the side of the lever, the thermal expansion induces a COM displacement along the cantilever oscillation direction. This is no longer true when the block is welded below the lever in a symmetric configuration; in this case the effective COM displacement along the lever oscillation direction is negligible. As a consequence, from the expression presented in equation (7), the oscillation amplitude in the asymmetric configuration is expected to be much more important than in the symmetric one. The use of two Ge crystals mounted in different positions is then crucial to validate the actuation mechanism based on COM-induced nanodisplacement.

For the system in figure 1(c), $l_0 = 13 \mu$m, close to half the Ge crystal thickness. For an intensity $I_0 = 7.4 \times 10^{10}$ ph s$^{-1}$ the temperature increase is found to be $\Delta T(\omega_0) = 0.24$ K. Using $\alpha_{Ge} = 5.9 \times 10^{-6}$ K$^{-1}$, according to equation (6), the induced COM displacement is $\Delta l(\omega_0) = 19$ pm. Using equation (7), with the measured quality factor of $86$ and the amplitude at resonance of $1.9$ nm, the COM displacement is found to be $\Delta l(\omega_0) = 22$ pm, which is consistent with the value calculated from equation (6). The error bar on the measured lever position is determined by the thermal fluctuations of the lever position and is $x(\partial T_{b}) = 1.6$ pm.

The system in figure 1(b) presents a much more symmetrical geometry. The $l_0$ value in this case must be smaller than the one in the case of figure 1(c), but it is not easily measurable. A rough estimate of the residual misalignment between the COM of the Ge microcrystal and the Si lever axis is the uncertainty in the FIB positioning device, which is about $1 \mu$m.

The distance $l_0$ that best fits the data while all other parameters are known is $1.5 \mu$m, which is indeed close to the precision of the FIB motor. The comparison between the model (equation (7)) and the measured oscillation is presented in figure 5 as the excitation frequency is swept from 100 to 2500 Hz. The agreement further establishes that the thermally forced displacement of the COM is at the origin of the observed lever oscillation equipped with the Ge crystal. Results for all configurations are then consistently explained using this single actuation mechanism. The MEMS actuation mechanism shown here can be extended to NEMS actuation. Considering

![Table 2. Correspondence between absorbed photon and oscillation amplitude for different levers and geometries. The top part presents the comparison for a coated and an uncoated lever with an asymmetrical geometry like in figure 1(c). The x-ray beam is here parallel to the direction of oscillation. The second part presents the comparison for an uncoated lever with a symmetric geometry. The x-ray beam is here either parallel or perpendicular to the direction of oscillation.](image)

![Figure 5. Response function of the lever shown in figure 1(b). The (black) curve presented is the measured amplitude of the lever oscillation as the beam intensity is modulated from 100 to 2500 Hz. The superposed (red) curve is the calculated expression using experimental parameters. The error bar on the theoretical (red) curve has been determined using Brownian motion. The theoretical (red) curve calculation involves the misalignment of the Ge microcrystal on the Si lever as the single adjustable parameter. In the inset a zoom on the resonant peak is presented.](image)
an Si lever of $1 \times 0.1 \times 0.1 \, \mu m^3$ and a Ge block of $100 \times 100 \times 100 \, nm^3$ with a thermal conductivity of $G = 3.7 \times 10^{-8} \, W K^{-1}$ and thermal capacity of $C = 1.7 \times 10^{-15} \, J K^{-1}$ [16] leads, according to equation (4), to a substantial temperature increase at a frequency in the MHz regime, typical for the resonance of such an NEMS. If a 1 $\mu W$ laser beam is absorbed in this Ge block, the induced thermal expansion will be several pm. As NEMS with lateral sizes close to 100 nm can exhibit quality factors of 1000, a forced COM oscillation with an amplitude of several pm can result at resonance in a nanometric NEMS oscillation amplitude. This is far larger than the thermally induced fluctuations of the NEMS position. This strategy of NEMS excitation can be compared to photothermal actuation based on thermally induced strain [17–23]. The essential difference is in the origin of the NEMS displacement. This origin is, in the mechanism that we propose, a strain-free thermally induced change in mass spatial distribution in an asymmetric structure.

We have demonstrated that the COM displacement mechanism is a very sensitive method to detect local temperature variation induced by low heating absorption. In the case of a highly asymmetric geometry we have shown it to be sensitive to an absorbed power of 10 $\mu W$ while the detection limit, given by the thermal noise ($k_B T$), is below 1 $\mu W$. This set-up is then a very good candidate for measuring low thermal flux in the near-field condition with high accuracy [24].

Furthermore the use of MEMS as Si single-crystal micro-oscillators can provide x-ray choppers at high frequencies. Using diffraction, an Si single-crystal MEMS appears to be a good candidate for the high frequency manipulation of x-ray microbeams. This could offer new tools either to change the phase x-ray wavefront, or to produce a rapidly modulated intensity of x-ray beams that are so important in real-time studies of fast dynamical processes in chemistry and in biology [25].

References

[1] Li M, Tang H X and Roukes M L 2007 Nature Nanotechnol. 2 114–20
[2] Ekinici K L, Huang X M H and Roukes M L 2004 Appl. Phys. Lett. 84 4469–71
[3] Yang Y T et al 2006 Nano Lett. 6 583–6
[4] Mamin H J and Rugar D 2001 Appl. Phys. Lett. 79 3358–60
[5] Cleland A N and Roukes M L 1998 Nature 392 160–2
[6] Rugar D, Budakian R, Mamin H J and Chui W 2004 Nature 430 329–32
[7] Burg T P et al 2007 Nature 446 1066–9
[8] Verbridge S S et al 2006 J. Appl. Phys. 99 124304
[9] Zwickl B M et al 2007 arXiv:0711.2263v1
[10] Arcizet O et al 2006 Nature 444 71–4
[11] Metzger C H and Karrai K 2004 Nature 432 1002–5
[12] Snigirev A, Kohn V, Snigireva I and Lengerer B 1996 Nature 384 49–51
[13] EXAFS-Data-Base-(Standards) (www.nsels.bnl.gov/beamlines/x18b/data.htm)
[14] Masujima T et al 1989 Rev. Sci. Instrum. 60 2522–4
[15] Krause M O 1979 J. Phys. Chem. Ref. Data 8 307–27
[16] Li D et al 2003 Appl. Phys. Lett. 83 2934–6
[17] Lavrik N V and Datskos P G 2003 Appl. Phys. Lett. 82 2697–9
[18] Sampathkumar A, Murray T W and Ekinici K L 2006 Appl. Phys. Lett. 88 2231041–3
[19] Koenig D R, Metzger C, Camerer S and Kotthaus J P 2006 Nanotechnology 17 5260–3
[20] Zhu Y, Corigliano A and Espinosa H D 2006 J. Micromech. Microeng. 16 242–53
[21] Geisberger A A, Sarkar M, Ellis M and Skidmore G 2003 J. Microelectromech. Syst. 12 513–23
[22] Que L, Park J S and Gianchandani Y B 2001 J. Microelectromech. Syst. 10 247–54
[23] Park J S, Chu L L, Oliver A and Gianchandani Y B 2001 J. Microelectromech. Syst. 10 255–62
[24] Mulet et al 2001 Appl. Phys. Lett. 78 2931–3
[25] Wulf M et al 1997 Nucl. Instrum. Methods Phys. Res. A 398 69–84