Thermal base drive for micromechanical resonators employing deep-diffusion bases

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Abstract

A novel approach of thermal excitation is presented, where thin micromechanical structures are suspended by deep-diffusion bases. Cantilevers and microbridges are fabricated, modeled and tested. Resonance frequencies are solely determined by the thin parts of the structures, and are independent of material properties and dimensions of the base. The efficiency for the amplitude of vibration is independent of the thickness and length of the base. Therefore short and thick bases can be applied, leading to relatively small temperature elevations inherent to thermal excitation.

Introduction

Micromechanical resonators have a wide application field for sensors as well as for actuators [1–3]. Up till now, two approaches have been applied for excitation and detection of the vibrations. One makes use of elements external to the resonator, exerting body or surface loads for excitation, and directly sensing displacements for detection. Examples are the electrostatic excitation and capacitive detection [4–7], and the Lorentz force excitation and inductive detection [8, 9]. A second approach makes use of elements integrated within the resonator. In this approach excitation of the mechanical vibration is achieved by forced deformation of the excitation element, and detection is obtained from the deformation of the detection element. Examples are piezoelectric excitation and detection [10–12], and thermal excitation and piezoresistive detection [13–16]. Neither of these approaches is ideal. A disadvantage of the approach with external elements is that a narrow air gap is required. This leads to limited room to move and to a large viscous damping due to squeezing of the air film, necessitating vacuum conditions. Also the gap puts requirements on the fabrication technology, and on the shape of the structure. In the approach with internal elements the materials of the driving elements are usually not optimized for mechanical properties, but instead for electrical and electromechanical transduction properties. Also, differential initial strains between these materials lead to initial bending and wrinkling of the structure. Furthermore, the initial strains can depend on operational conditions, such as the static temperature elevation in the case of thermal excitation [17].

A novel approach to the excitation and detection of the mechanical vibrations of micromechanical structures, called 'base drive', was presented in ref 18. In this approach the driving elements are embedded in the base or support of the micromechanical structure, while the compliant part of the structure is of a simple geometry, and consists of a single material only. Different configurations were investigated. Figure 1 shows the example of a bending base drive with thermal excitation, where the base is realized by deep boron diffusion and p-+ etch stop [19]. When the base is forced to

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Fig 1 Sketch of cantilever with deep-diffused base with thermal excitation

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bend downward, a displacement and a rotation are imparted on the suspended edge of the compliant part of the structure. Due to distributed inertial and damping forces, the latter will deform, and will vibrate with large amplitudes for frequencies around its natural frequencies [18, 20]. It is expected that for proper designs of the base and of the compliant part the resonance frequency of the structure will be determined by the material properties and dimensions of the single material compliant thin part of the structure.

Other authors have already pointed at advantages of a thick rim realized by deep boron diffusion, such as the relevant planar dimensions of the structure being determined by front side processes [21], and sharp corners with stress concentration being avoided [22, 23]. But for thermal excitation there are additional advantages in having the excitation at the thick base. With the heat generation close to the support, and on a thick part of the structure, the thermal conductivity to the heat sink is expected to be large, and the resulting static temperature elevation, often a problem in thermal excitation [17], will be small. Moreover, between limits, the efficiency of thermal excitation does not decrease with increasing thickness and decreasing length of the base. If we assume a homogeneous base with heat generation located in the upper fibres, then the effective bending moment will have a magnitude $M_e$ proportional to the flexural rigidity and independent of frequency for frequencies below a threshold frequency $\nu_0 = 2a/h_b^2$ [24], with $a$ the coefficient of thermal diffusivity of the base material and $h_b$ the thickness of the base. For silicon $a = 6.2 \times 10^{-5}$ m$^2$/s, so that for $h_b = 15\ \mu$m the threshold frequency equals $\nu_0 = 550$ kHz. The bending moment causes a rotation which is now independent of the thickness and length of the base, and is even independent of the length of the drive resistor! This means that for a 1 $\mu$m thick 'base' the rotation would be the same, only the threshold frequency would be much larger.

Thermal base drive is attractive for several applications, such as resonant strain gauges, resonant proximity sensors, ultrasonic actuators and vibrating mirrors. The resonance frequency is determined by the bare (simple and homogeneous) structure, and will therefore be more stable and more selectively sensitive than in the case of conventional drive. Also, quality factors can be higher because of the absence of thin films of poor mechanical quality, and the absence of nearby external elements (squeeze film damping). Large forces or large displacements can be obtained, although this strongly depends on the geometries of the compliant part of the structure and of the base, respectively. This paper presents the realization of thermally excited cantilevers and microbridges suspended from deep boron diffused bases. Models are derived for the thermal and mechanical behaviour of these structures, and these are verified by experiments.

**Fabrication**

Test samples were fabricated from (100) silicon wafers, see Fig 2. Consecutive processing steps are:

1. Thermal oxidation (wet atmosphere, 1100 °C, 3 h)
2. Opening of diffusion windows (buffered HF)
3. Double sided deep boron diffusion (solid source, 1150 °C, 16 h)
4. Opening of diffusion windows (buffered HF)
5. Shallow boron diffusion (solid source, 1150 °C, 40 min)
6. Oxide strip (HF solution)
7. Deposition of insulating layer (LPCVD silicon oxide)
8. Opening of contact windows and of etch windows (buffered HF)
9. Metallization (evaporation of chromium-gold, lift-off)
10. Bulk etch (EDP solution, 115 °C, 1 h)

The contours of the diffusion regions sketched in Fig 2 are the expected positions of the boron concentration required for the etch stop (5 x 10$^{19}$ cm$^{-3}$ [25]). In the area where the shallow and deep diffusion regions overlap, superposition of the two profiles results in a smoothing of the aforementioned contour. This smoothing effect will also occur where the thick base and the thick rim meet. Exposed sharp outer edges of the diffusion profile such as at the tip of the cantilever and the edge of the rim are smoothed during the etching of the bulk.

Fig 2. States in the fabrication sequence after deep boron diffusion (a), after shallow boron diffusion (b), after metallization (c), after bulk etch (d).
Figure 3 shows SEM photographs of realized structures. Figure 3(a) shows an array of structures with 3.2 μm thick and 293 μm microbridges suspended by 15 μm thick bases 52 μm long. Figure 3(b) shows a close-up of the top side of a 15 μm thick base of length 25 μm. It also shows the dielectric layer with contact holes and metallization. Note the thick rim from which the base is suspended. This photograph clearly shows the rounded shapes obtained with the diffusion based etch stop layer. Figure 3(c) shows a close-up of the bottom side of a thick base of length 55 μm. It also shows the thick rim around the periphery of the etch hole. This thick rim determines the lateral dimensions of the etched hole, and therefore allows for large differences in wafer thickness.

Cantilevers

Model

For excitation of the cantilevers, a voltage \( V + v \exp(j\omega) \) is applied across the resistive drive element with resistance \( R \), leading to a dynamic power dissipation with a component of magnitude \( P_0 = 2Vv/R \) at the excitation frequency [14]. This leads to an effective bending moment with magnitude \( M_0 = xEI_bP_0/(\lambda A_R) \) for frequencies below the threshold frequency \( \nu_t = 2a/h_b^2 \) [24], with \( x \) the linear thermal expansion coefficient of the base material, \( EI_b \) the flexural rigidity of the base, \( \lambda \) the coefficient of thermal conductivity, \( A_R \) the area of the resistor (width times length), \( a \) the thermal diffusivity and \( h_b \) the thickness of the base material (we assume that the dissipation is concentrated in the upper fibres of the cross section). The bending moment \( M_0 \) causes a rotation \( \phi_c = 6aP_0/(\lambda h_b) \), with \( h_b \) the width of the base. This leads to a nominal rotation \( w'(0) = \phi_c \) and a deflection \( w(0) = \phi_c I_c \) at the end of the base, with \( I_c \) the distance between the centre of the drive element and the end of the base. This causes a forced vibrational motion \( w(x) \exp(j\omega t) \) of the flexural cantilever of length \( L \), flexural rigidity \( EI \), mass per unit length \( pA \) and drag force per unit length \( c \), with \( x \) the distance to the edge of the drive element. Distributed inertial and damping forces \( pA\ddot{w}(x) + cw(x) \) act as a distributed transverse load on the cantilever. An expression for \( w(x) \) of the resulting vibration can be derived from [20]

\[
\begin{align*}
    w(x) &= w(0) \left(1 + \sum_{i=1}^{\infty} a_i X_i(x)(H_i(j\omega) - 1)\right) \\
    &+ w'(0) \left(x + \sum_{i=1}^{\infty} \beta_i X_i(x)(H_i(j\omega) - 1)\right)
\end{align*}
\]

(1)

where \( X_i(x) \) is the shape function of the \( i \)th mode for \( 0 \leq x \leq L \) (\( X_i(x) = 0 \) for \( x < 0 \))

\[
X_i(x) = \cosh(k_i x/L) - \cos(k_i x/L) - \sigma_i (\sinh(k_i x/L) - \sin(k_i x/L))
\]
with $k_i$ the $i$th root of $1 + \cosh(k_i) \cos(k_i) = 0,$
\[ \sigma_i = \frac{(\cosh(k_i) + \cos(k_i))}{(\sinh(k_i) + \sin(k_i))} \]
\[ \alpha_i = \int X_i \, dx/L = 2\sigma_i/k_i \]
and
\[ \beta_i = \int X_i \, x \, dx/L^2 = 2/k_i \]
so that $k_1 = 1.875$, $\sigma_1 = 0.734$, $\alpha_1 = 0.738$, $\beta_1 = 0.569$
and $X,(L) = 2H,(j\omega)$ is the second order transfer function
\[ H,(j\omega) = \frac{1}{1 + (j\omega/\omega_0)^2} \]
with $Q_0$ the quality factor of the $i$th mode For practical values of $Q_0$ only one term needs to be considered
near the $i$th resonance frequency of the cantilever $v_i = 1/(2\pi)k_i^2\sqrt{(EI)/(\mu A)/L^2}$

The vibration of the cantilever causes a transverse
reaction force and a bending moment exerted on the
base. The reaction loads are found from integration of
the distributed inertial and damping forces over the
length of the cantilever. This gives an additional deformation
of the base superimposed on the forced curvature
due to the driving moment. Figure 4(a) shows the
predicted results for the modulus of the normalized
tip deflection $|w(L)/(|\phi_x|)|$ versus normalized resonance frequency $v/v_i$. This particular plot was generated with a value $Q_0 = 100$. The plot shows a maximum value of magnitude $|w(L)/(|\phi_x|)|_{\text{max}} \approx 2(\beta_1 + (L_e/L)x_i)Q_1$, at
nearly the resonance frequency $v \approx v_i$, and a bandwidth of $v_i/Q_1$ at the $-3$ dB level. Also shown is the simulated result of the bending strain $\varepsilon_0$ in the upper fibres at the centre of the drive element due to the vibrational load, divided by the nominal rotation $\phi_0$. The maximum value equals $|\varepsilon_0/\phi_0|_{\text{max}} \approx (1/2)(h_b/L)k_i^4(\beta_1 + (L_e/L)x_i)^2Q_1$.

The vibration induced strain causes a change in the resistivity of drive resistor thanks to the piezoresistive effect. Figure 4(b) shows the Bode plot of the phase of the impedance of the piezoresistive driving element. For frequencies far away from resonance the impedance is equal to the resistance $R$. As a result of the deformation of the drive element due to the vibrational load, a loop emerges. The resulting maximum phase shift equals
\[ \Delta \phi_{\text{max}} \approx (180/\pi)G(2V^2/R)(\lambda h_e) \]
\[ (1/2)(h_b/L)k_i^4(\beta_1 + (L_e/L)x_i)^2Q_1 \]
where $G$ is the gauge factor of the resistor material. For structures with a relatively compliant base decreases are
found for the resonance frequency, tip deflection and
phase shift of the impedance, with relative magnitudes of $3(EI/L)/(EI_0/L_0)$, $3.33(EI/L)/(EI_0/L_0)$ and $8(EI/L)/(EI_0/L_0)$, respectively.

Experiments

Transfer functions and impedances were measured
using an HP 4194 A network analyzer. The displacement
of the cantilever was monitored using a Michelson
interferometer. Figure 5(a) shows a Bode plot of the measured transfer function of the displacement of the
tip of a thermally excited cantilever (C1) of length
800 µm and thickness 3 µm, suspended by a base of
length 100 µm, width 100 µm and thickness 15 µm, and distance between resistor and the end of the base
$L_e = 35$ µm. The driving power required to get an amplitude of vibration equal to one fringe (approx. 80 nm)
was determined. It turned out that the structures have a built-in dc offset of approx. 5 mV. Impedance
measurements, as well as single-element two-port approach measurements [26], failed to show any response, even
under vacuum conditions and with 1.3 V dc voltage.
Therefore, to test the capability of piezoresistive detection,
experiments were performed with acoustic excitation
using a loudspeaker, and keeping the amplitude of vibration of the tip of the cantilever at resonance at one
or more fringes. The on-chip resistor was connected in
a balanced Wheatstone-bridge. Figure 5(b) shows a
Bode plot of the bridge output for a similar sample
(C2) of length of 400 µm in acoustic excitation. The
amplitude of vibration was kept at one or more fringes. The on-chip resistor was connected in
a balanced Wheatstone-bridge. Figure 5(b) shows a
Bode plot of the bridge output for a similar sample
(C2) of length of 400 µm in acoustic excitation. The
amplitude of vibration was kept at one or more fringes.

Table 1 summarizes the results obtained from these
measurements.

In general the experimental results agree reasonably
well with the predicted values. The efficiencies of excitation and detection are higher than predicted. This is
remarkable because in the model it was assumed that
Microbridges

Still the static part of the dissipation is expected to cause a static temperature elevation of the structure. This temperature elevation is expected to be much smaller for thermal excitation at a thick base compared to conventional thermal excitation. Experiments were carried out on microbridges of lengths 893 μm, suspended by two identical thick bases. Of the latter the distance \( L_e \) between the centre of the resistor and the end of the base was constant, while the distance \( L_Q \) between the resistor and the support (a thick rim) was varied. Detection of the vibration at the centre of the microbridge was achieved using a Michelson interferometer. An HP 4194 A network analyzer was used to measure the frequency response. From this the frequency at the first resonance mode was determined. For each sample the driving voltages \( V \) and \( v \) were varied. This results in varying static dissipations \( Q = (V^2 + 0.5v^2)/R \) [14]. Figure 6(a) shows the measured resonance frequency versus static heat \( Q \) The influence of the static heat generation on the resonance frequency stems from the temperature elevation of the structure due to the heat generation. The temperature elevation is expected to be smaller for smaller distances \( L_Q \) of the heat source to the heat sink. The temperature elevation leads to a thermal expansion of the thin microbridge as well as of the thick base. This expansion causes a compressive axial force in the structure. This force is superimposed on the initial tensile axial force inherent with boron doping, and hence causes a shift of the resonance frequency of the structure. For a large range of axial forces \( N \), the second power of the resonance frequency is linear with the axial force [27]

\[
\Delta(\nu_{\text{res}}^2) = -0.312 \frac{E}{\rho L^2 A} \frac{1}{N}
\]

Figure 5 Experimental results Bode plots of tip displacement of sample \#C1 in thermal excitation (a), and of piezoresistive detection of sample \#C2 in acoustic excitation (b)

the electrical current is located in the upper fibres of the cross section of the drive element, while in practice the current flow is probably more three-dimensional. The resonance frequencies found in acoustic excitation were a few percent lower than observed in experiments with thermal excitation. In thermal excitation the resonance frequency was very stable, and hardly dependent on d.c. power.

### TABLE 1 Experimental and predicted results for cantilevers with thermal excitation at deep-diffusion base

<table>
<thead>
<tr>
<th>Sample</th>
<th># C1</th>
<th># C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (μm)</td>
<td>800</td>
<td>400</td>
</tr>
<tr>
<td>Resistance drive element (Ω)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Fundamental resonance frequency (kHz)</td>
<td>(5.82)</td>
<td>(23.3)</td>
</tr>
<tr>
<td>in thermal excitation</td>
<td>6.304</td>
<td>24.66</td>
</tr>
<tr>
<td>in acoustic excitation</td>
<td>6.334</td>
<td>23.91</td>
</tr>
<tr>
<td>Quality factor</td>
<td>62</td>
<td>138</td>
</tr>
<tr>
<td>Tip displacement at resonance (nm/mW)</td>
<td>160 (57)</td>
<td>50 (63)</td>
</tr>
<tr>
<td>Bending strain drive element</td>
<td>( \Delta R/R = 2 \times 10^{-3} )</td>
<td>( \Delta R/R = 8 \times 10^{-3} )</td>
</tr>
<tr>
<td>at 80 nm tip displacement</td>
<td>( (\epsilon_b = 3.5 \times 10^{-6}) )</td>
<td>( (\epsilon_b = 1.4 \times 10^{-6}) )</td>
</tr>
<tr>
<td>Maximum phase shift, ( \epsilon_p ) (mdeg)</td>
<td>(0.1)</td>
<td>(0.6)</td>
</tr>
</tbody>
</table>

Base thickness \( h_b = 15 \) μm, length \( L_b = 100 \) μm, width \( b_b = 100 \) μm, distance between resistor and end of base \( L_e = 35 \) μm. Cantilever thickness \( h = 3 \) μm, mass density \( \rho = 2.33 \times 10^3 \) kg/m³, Young’s modulus \( E = 1.7 \times 10^{11} \) N/m². Predicted values in parentheses.
Figure 6 shows a plot of the predicted and measured frequency shift per mW heat generation versus distance \( L_Q \). The measured curve shows the same trend as the predicted curve, only the slope of the measured curve is smaller than predicted. Both discrepancies are probably caused by the influence of the thickness of the layer. In order to obtain varying distances \( L_Q \), we simply varied the width of the layer in our mask layout. Hence, a smaller value of \( L_Q \) is accompanied by a larger thermal resistance of the layer. The latter was not accounted for in our model. For structures without the thick layer, the frequency shift is expected to be smaller. For larger values of \( L_Q \), the measured curve drops below the predicted curve. One possible explanation might be that heat transfer directly to the surrounding air plays a role. However, we think that this decrease of the slope stems from the effect of a small initial deflection of the microbridge, which leads to a smaller impact of the thermal expansion than expected according to eqn (2) [27].

Discussion

The resonance frequencies are almost exclusively determined by the flexural structures. The tip displacement is almost independent of the stiffness of the cantilever. Magnitudes in the order of 1 µm are easily obtained. Detection of the vibration at the base has a low sensitivity, proportional to the ratio of stiffnesses of the cantilever and of the base. Even so, strains at the base in the order of \( 10^{-5} \) are easily obtained, which could be sufficient.

To get any excitation, the drive element should have a finite stiffness. The efficiency of detection at the base is even proportional to the ratio of stiffnesses of the cantilever over stiffness of the drive element. But if the drive element is too compliant it becomes part of the flexural structure, and it will affect the device characteristics such as the resonance frequency and tip displacement. Therefore, we should define 'base drive' as the drive with negligible effect on device characteristics. In this sense, the excitation applied by Brennen et al [7] is 'base drive', while that applied by Moser et al [16] is not.

'Base drive' is suitable both for resonant sensors as well as for actuators. The resonance frequency is determined by a bare (simple and homogeneous) structure, and will therefore be more stable and more selectively sensitive than in the case of conventional drive. Also, quality factors can be higher because of the absence of thin films of poor mechanical quality, and the absence of nearby external elements (squeeze film damping). Large forces or large displacements can be obtained, although this strongly depends on the geometry of the flexural cantilever and of the base, respectively.

The fabrication of the devices is simple and requires only 5 masks, or even 4 masks if bulk etching is done from the front side [18]. The forced rotation of the base is independent of the thickness and the length of the excitation area. Therefore the carrier of the thermal excitation element may as well be thick and the resistor may as well be close to the substrate. This way the thermal conductance to the substrate is large, so that the temperature elevation of the structure, often a drawback of thermal excitation [17], will be small. Alternatively, a relatively large excitation power can be applied without thermal breakdown of the resistor. This makes thermal excitation at a thick base useful even for actuators for which a large amplitude of vibration is required.

The efficiency of thermal excitation and piezoresistive detection will probably be higher if thin film resistors on top of the base are used, rather than having dissipa-
tion in the bulk of the p⁺ base as we have done in the investigated samples. Current research focuses on samples with polysilicon resistors.

Conclusions

The novel approach of thermal excitation employing deep-diffusion bases was presented. Device characteristics such as resonance frequencies and amplitudes of vibration can be independent of the geometry of the drive element, while the efficiency of detection at the base is proportional to the ratio of stiffnesses of the compliant structure and the drive element. Static temperature elevations are smaller than for conventional temperature elevations are smaller than for conventional structures with thermal excitation with equivalent power dissipations. Larger voltages and currents can be allowed without disturbance of device performance. A tip displacement of 1 μm and a detection strain of 10⁻⁵ are easily obtained.

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