THE PHYSICS OF MICROMETER STRUCTURES

Microelectromechanical systems, in short MEMS, are small systems embedded in silicon wafers. The ongoing miniaturisation of electronic circuits is making it possible to incorporate a whole range of functionalities. One example of this is the MEMS resonator, a miniature 'tuning fork'. During MEMS production, a wide range of small variations occur which can affect the physical properties of the component. To get a clearer picture of these effects, numerous aspects of the MEMS resonator were simulated using modern FEM software.

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MEMS components are a combination of electronic, mechanical and sometimes chemical components, which perform a particular role. NXP Semiconductors in Nijmegen, the Netherlands, developed a MEMS resonator made of silicon material, and special etching techniques in the wafer fab have made it possible to create a miniature resonator or 'tuning fork'. This resonator in the wafer can replace the antiquated quartz crystal, which determines the oscillation frequency in nearly all electronic systems. These old crystals tend to be no smaller than 1 mm^3, which is pretty sizeable and relatively expensive. A MEMS resonator can easily be included in the electronic design of a chip with dimensions of around 10 x 20 x 40 μm^3. In a wafer fab, deposition and etching techniques are used to add a whole range of structures to a chip. As such, creating a MEMS resonator is one of the options.

Quartz crystal is a tried and tested technology, and the frequency of the crystals remains stable for years. If one manufactures the equivalent in the shape of a MEMS resonator, it then has to meet various requirements to generate frequency signals with low noise, a high Q factor and low temperature drift. The MEMS resonator designed by NXP meets all of these requirements.

The manufacturing process for MEMS components causes a range of small variations. For instance, chip depth variations can occur during deposition or layer etching, which can affect certain properties of the resonator.

AUTHOR'S NOTE

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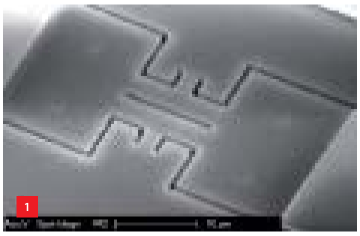
Physixfactor has simulated a series of these types of effects on a so-called dogbone resonator and mapped out the dependency of a few properties. These simulations were carried out using COMSOL's Finite Element Method software. Using this software, a whole range of physical couplings were simulated, e.g.:

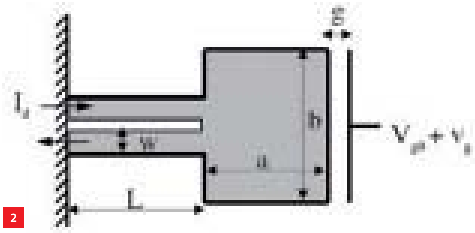
- Nonlinear oscillations
- Anchor losses (or acoustic losses)
- Mode coupling, etc.
- Thermal losses during oscillation
- Resonance drift resulting from temperature fluctuations
- Damping losses resulting from small air leakages in the packaging
- Nonlinear electrical forces driving the resonator
- Influence of the thickness of the oxide layers on the resonator
- Dimensional variations of the dogbone resonator

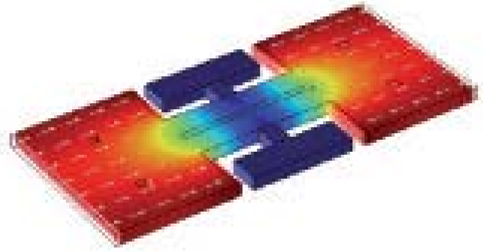
To produce a MEMS resonator that meets the set requirements, one needs to carry out simulations to understand how to dimension the resonator to ensure long-term stable and reliable operation. This will help to draft a set of manufacturing requirements. This article will outline a few simulations in more detail.

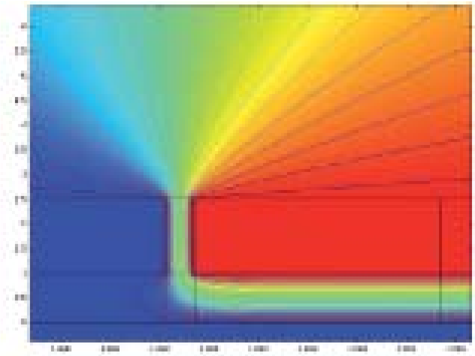
Nonlinear oscillations

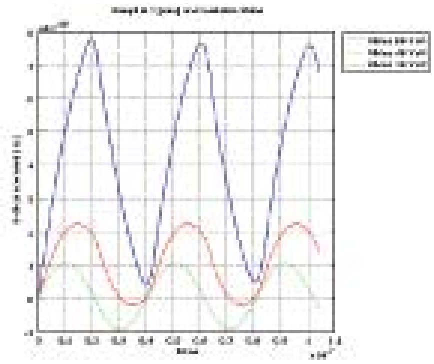
Figure 1 is an SEM photo of the MEMS resonator in question; the scale indicates that the resonator is approximately 40 microns long. The resonator is driven into oscillation using a sinusoidal voltage, and once the











frequency of the electrical signal matches the longitudinal oscillation mode of the resonator, the resonator will be wound up.

A constant bias voltage V_{DC} is applied accross the gap (figure 2) in the material, on top of which is a sinusoidal signal V_{AC}. The time-dependent electrical force across the gap can be written as:

$$F_{el} = \eta V_{AC} \sin(\omega t) + \frac{V_{DC}\eta x}{g} \quad (1)$$

where η is a constant, reflecting the coupling between the electrical and the mechanical domains, V_{AC} the alternating voltage, ω the angular frequency of the signal, V_{DC} the bias voltage, x the displacement of the resonator and g the gap. The frequency can be calculated from the differential equation of this nonlinear oscillation:

$$f_{res} = \sqrt{\frac{k}{m} - \frac{V_{DC}\varepsilon_o wh}{mg^3}} \quad (2)$$

Where k is the spring constant of the resonator, m the mass of the vibrating part, ε_0 the dielectric constant, w the width of the gap and h the height of the gap. If the bias voltage varies, this can be used to alter the frequency of the system. Increasing bias voltage causes the frequency of the system to decrease. This can be used to tune the system to the correct frequency, for instance. It should be noted, however, that the resonator being discussed here had a typical resonator frequency of 56 MHz. The orientation of the resonator in relation to the crystal axes in the silicon also plays a role

1 *SEM photo of the resonator.*
2 *Diagram of the dogbone resonator. A sinusoidal signal drives the resonator across the gap g. The forces are not linear; they are heavily reliant on the size of the gap.*
3 *The red parts move symmetrically in relation to each other in the longitudinal mode.*
4 *Fringing of the potential lines across the gap.*
5 *Nonlinear behaviour at V_{DC} = 80 V, blue curve.*

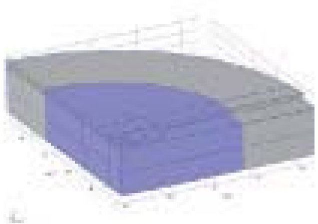
because the Young's modulus in the [100] and [110] directions is different and, moreover, nonlinear; this makes it even more complicated to tune the system [1] [2] [3].

The first time the system is in a state of vibration, the dogbone resonator will oscillate symmetrically in longitudinal mode (see Figure 3). The blue parts will not oscillate, while the red parts will display amplitude, indicated with grey arrows. Figure 4 shows the fringing effect of the electrical potential lines across the gap of the resonator. This gap can be viewed as a condenser, with opposing charges exercising force on each other (see Equation 1).

The 3D structure of the resonator has been programmed into the FEM software and a time-dependent simulation has been carried out to study the nonlinear effects. Figure 4 shows a few oscillations of the dogbone resonator at various V_{DC} values. The nonlinear oscillation at V_{DC} = 80 V is clearly perceptible. The green line is more or less sinusoidal at V_{DC} = 10 V; the blue line is the highly nonlinear oscillation at 80 V. In this case, the FEM simulation is time-dependent and the intervals are approximately 1.5 nanosecond. The amplitude is then nearly 0.1 nanometer.

Anchor losses

The anchors of the resonator fix it to the environment of the chip. If the resonator is in a state of resonance, the anchors will lose energy, and these mechanical losses will contribute to the system's Q factor declining. These losses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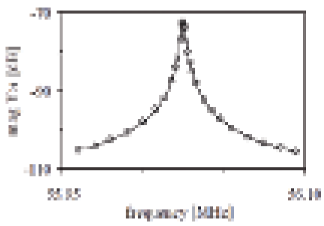
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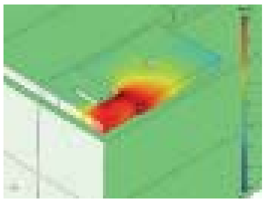
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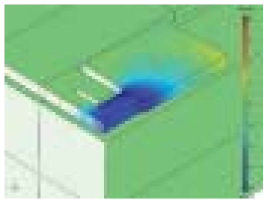
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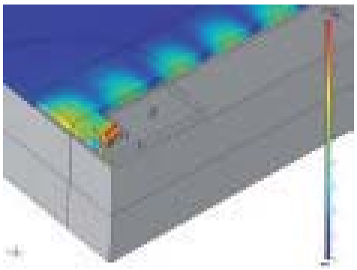
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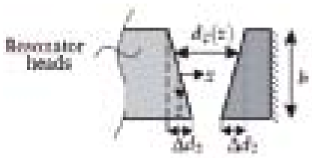
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6 *Calculation of anchor losses.*
(a) Blue is the silicon and grey are the Perfectly Matched Layers which completely absorb the oscillation energy.
(b) Q factor.

7 *Anchor losses due to an oscillation. The yellow-green lobes reflect the amplitudes that occur in the geometry and disappear into the environment via the anchor.*

8 *Asymmetric gap, possible source of mode coupling.*

9 *Temperature variations in the anchor due to high-amplitude oscillation.*
(a) The compression cycle; the red part represents heating (higher temperatures).
(b) The elongation cycle; the blue part represents cooling off (lower temperatures).

have been calculated using the COMSOL software, for which a quarter of the model is enough. The blue parts in Figure 6a are the normal silicon material, while the grey parts are the so-called Perfectly Matched Layers, which completely absorb the acoustic energy. This allows the calculation of the system's Q factor in a time-dependent simulation. Figure 6b shows a diagram of the Q factor around the basic frequency of 56 MHz.

The anchor losses are nicely illustrated in Figure 7 and are highly dependent on the dimensioning of the anchor itself. To map out the effects of the dimensioning, it is important to carry out a minute parametric study for the manufacture of the resonator.

Mode coupling

If the dogbone resonator is not properly dimensioned, and the V_{bias} induces major nonlinear behaviour, mode coupling may occur. It is therefore important that other oscillation modes are not too close to the longitudinal frequency. For instance, it is important that the gap, across which the voltage is driving the oscillations, is nice and even. Current etching techniques are certainly capable of achieving this, but sometimes the gap can taper off too much. The parts that are not as far apart will attract each other more than the parts that are further removed from each other. This asymmetry may cause mode coupling (see Figure 8).

Thermal losses

If the resonator is excited particularly hard and the amplitudes are relatively high, instantaneous heating and cooling off at the anchor will occur (see Figure 9). As a result, the material at the anchor will be subject to a cycle of pressure and axial tension. This goes hand in hand with a cycle of warming up when under pressure and cooling down in the tensile stress phase. This process will be fast at 56 MHz and the warming up and cooling down cycles will offset each other. Nevertheless, a little bit of energy will always be lost; for instance, in the warming-up cycle, a small amount of heat will flow into the surrounding material via the anchor. This loss of energy will reduce the Q factor of the system.

'Multi-physics'

Modern FEM software is capable of simulating many aspects of the MEMS resonator and can, in fact, be regarded as a laboratory in which people can 'measure' or forecast a whole range of product properties. Numerous test runs were performed on the computer, the results of which always translated to the specifications of the factory production processes. A range of variations in the production process could be simulated and understood using the COMSOL software. A sound knowledge of physics is, however, imperative to choose the right simulations to be able to generate the effects that can be observed in practice.

Acknowledgement

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