PHENOMEN

PHENOMEN PROJECT: All-Phononic Circuits Enabled by Opto-mechanics	
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WP3: Integration and Validation	
Deliverable D3.3 **Effects of stress fields on the mechanical Q in phononic devices**	
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Abstract

The effect of strain on the properties of 1-dimensional optomechanical cavities made of nanocrystalline silicon is investigated. The strain of the nanocrystalline films, ranging from 30 to 300 MPa in these experiments, is controlled by the annealing temperature of the as-deposited amorphous films. The optical Q factor of the nanocrystalline devices is by a factor of five lower than in the devices made of single crystalline silicon at room temperature. Surprisingly, and contrary to the expectations, the mechanical Q factor is two to three times higher in nanocrystalline devices compared to single crystalline devices, increasing with the annealing temperature and decreasing strain. In addition, the results show that the optical absorption of nanocrystalline cavities is very efficient and the thermal conductivity small, leading to large modulation of the temperature of the cavities and, consequently, proving that nanocrystalline silicon is a promising material for optomechanical devices exploiting non-linear effects.

References

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Version 1	18/08/2018		Initial Version
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Contents

1. Introduction/background

A recent publication by the PHENOMEN consortium shows that nanocrystalline silicon (nc-Si) is a very promising material in optomechanical applications [1]. Although nc-Si has a lower optical Q-factor as compared to crystalline silicon, the mechanical Q-factor is a few times higher and the non-linear effects are more pronounced, promoting functions like self-pulsing and phonon lasing at room temperature. Elastic strain can be used to further enhance the mechanical Q factor and to increase the operation frequencies, as reported for one-dimensional SiN phononic crystals, where Q factors up to 800 million have been measured [2]. The stress of nc-Si can be easily tuned from a few tens of MPa to a few hundreds of MPa by annealing temperature of the as-grown amorphous silicon layer [3]. Here we investigate the effect of stress, or strain in released structures, on the properties of nc-Si optomechanical cavities.

2. Description of the deliverable

"Effects of stress fields on the mechanical Q in phononic devices". The target of this deliverable is to investigate the effect of stress fields on optical and, especially, on mechanical properties of 1-dimensional nanocrystalline optomechanical cavities.

3. Progress towards objective

Nanocrystalline films with various amount of tensile stress were produced and the stress measured at VTT. The mechanical properties, e.g., the sound velocity, were measured by picoacoustic methods at MENAPIC. One-dimensional optomechanical cavities were fabricated at UPV using e-beam lithography and HF etching. The devices were measured at ICN2 to determine the Q factors. In addition, the effect of strain on the mechanical properties of the cavities was investigated by FEM simulations at VTT.

4. Results

The nominal structure of the nc-Si SOI-like wafers was designed to have a 220 nm thick nc-Si film on a 1000 nm thick oxide layer. The fabrication process included growth of the thick SiO_2 by wet oxidation at 1050 °C and a layer of amorphous Si (a-Si) at 574 °C by chemical vapour deposition (CVD). Amorphous Si deposited by CVD is typically under compressive stress and is not as such suitable for released structures. To convert the compressive stress to tensile, the wafers were annealed at temperatures from 650 °C to 950 °C for 60 min. The compressive stress of the as-deposited amorphous film changes to tensile stress during annealing, see Fig 1, and the amount of stress can be controlled by the annealing temperature and time. The measured thickness of the SiO_2 layer is 1013 nm. The thickness of the a-Si and nc-Si (after annealing) are given in the table below. As seen, the thickness of the film decreases a little during annealing, showing that recrystallization of the amorphous film occurs, leading to a decrease in film volume and, consequently, to changing the stress from compressive to tensile.

Table 1. *Thickness of the as-deposited a-Si and annealed nc-Si films.*

Sample	Thickness (nm) (Filmtek)	Refractive index@632nm (Filmtek)
a-Si (monitor)	218 ± 4	4.39 ± 0.03
a-Si (monitor)	215 ± 4	4.36 ± 0.03
Anneal 750 C (monitor)	212 ± 3	3.87 ± 0.02
Anneal 950 C (monitor)	212 ± 4	3.87 ± 0.02

The stress was determined by comparing the bending of the wafers before and after annealing. For the stress measurements, specific 300 μm thick double side polished wafers were used. The annealing step transforms the amorphous film to nanocrystalline, with the grain size ranging from a few nm to 100-200 nm. The specific microscopic nature of the nanocrystalline material has a direct impact on the optical losses, i.e., light scattering from the crystalline domain interfaces, and on the thermal conductivity by affecting the phonon mean free path due to the grain boundary scattering.

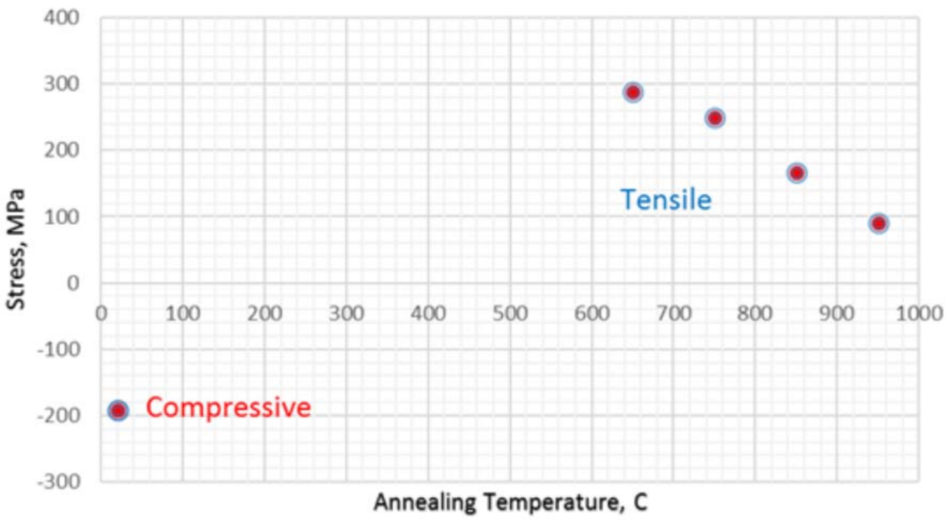

Fig. 1. *Measured stress in nc-Si films annealed at different temperatures. The compressive stress of the original amorphous film changes to tensile by annealing and the tensile stress decreases as a function of the annealing temperature. The annealing time was 60 minutes for all the wafers.*

Picoacoustic characterisation

The mechanical properties of the nc-Si films were characterised using picoacoustic method at MENAPIC. A thin layer, 12 nm, of Al was deposited on the sample to act as an absorber. Femtosecond laser pulses were made to impinge on the samples and the echo was measured, see Fig. 2. From the echo, when the layer thickness is known, the speed of sound can be deduced. The results are given in the Table 2 below. The speed of sound in nc-Si is higher than in (100) c-Si, which can be explained by the mixture of (100), (110) and (111) crystallographic directions in the nc-Si films. Interestingly, the speed of sound does not depend significantly of the annealing temperature, i.e., the stress. The speed of sound in the a-Si sample is higher than reported in the literature and needs further investigation.

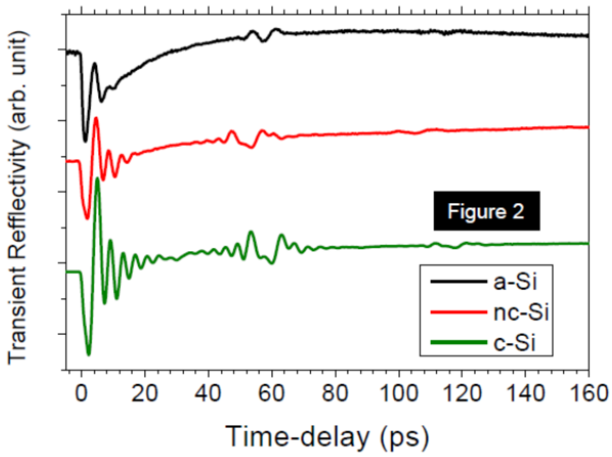

Fig. 2. *Time-of-flight scans measured from amorphous, nanocrystalline and crystalline (100) silicon. The measurements show that the sound velocity in nc-Si is higher than in (100) c-Si.*

Table 2. *Velocity of sound of nc-Si films annealed at various temperatures.*

Sample description			MENAPiC Measurements			
Reference	Anneal Temperature	Top layer thickness (nm)	Top layer TOF (ps)	Top layer + silica TOF (ps)	Top layer sound velocity (m/s)	Silica thickness* (nm)
#1	650°C	220	53,8	394,1	9053	1016
#2	750°C	220	53,4	393,9	9129	1016
#3	850°C	220	53,8	394,1	9053	1016
#4	950°C	220	53,1	393,3	9186	1015
#5	no anneal	220	56,9	396,4	8511	1013

* assuming sound velocity in silica 5950 m/s

Optomechanical properties

One dimensional optomechanical cavities were fabricated at UPV on the wafers with different tensile stress. The design was the same as reported for OMCs in c-Si [4] and nc-Si [2] for easy comparison of the effect of strain. A SEM image of an OMC is shown in Fig. 3.

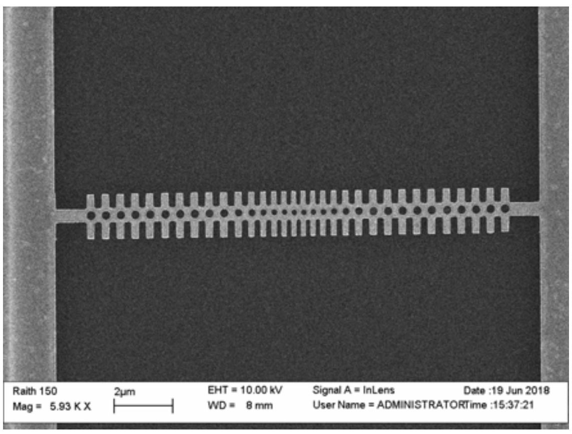

Fig. 3. *SEM image of a one-dimensional optomechanical cavity made of nc-Si annealed at 950 C. The thickness of the beam is 212 nm.*

The OMCs were characterised at ICN2 at room temperature and atmospheric conditions on an anti-vibration stage. The measurement set-up is shown in Fig. 4. A tapered optical fibre is placed in close proximity to the OM beam and the evanescent wave couples to the OM cavity modes.

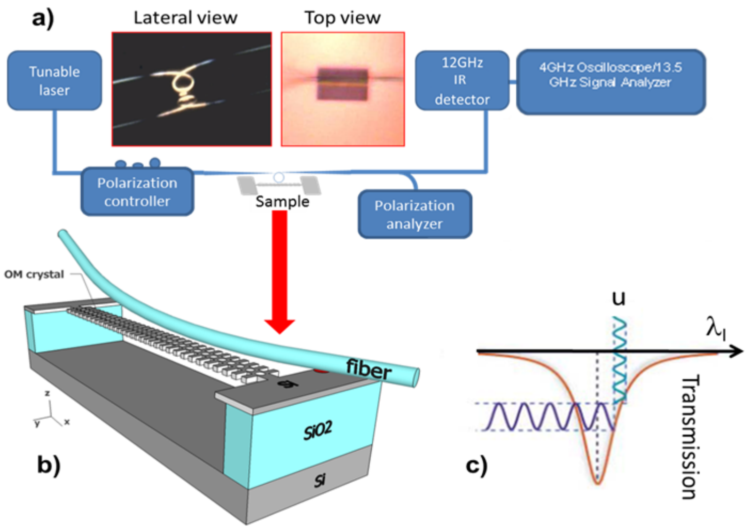

Fig. 4. *Sketch of the experimental setup to measure the optical and mechanical properties of the OMC. The sample size has been greatly increased for clarity. The top left photograph shows a lateral view of the real microlooped tapered fibre close to the sample, where the fibre can be seen reflected on the sample. The top right photograph shows a top view of the tapered fibre placed parallel with the OMC and in contact with one of the edges of the etched frame.* ***b)****. Relative positioning of the tapered fibre and the OMC. The leaning point of the fibre is highlighted in red. The fibre is placed close enough to the central part of the OMC to excite efficiently its localized photonic modes.* ***c)*** *Scheme of the transduction principle.*

The **optical** transmission spectra at low and high photon occupation and the deduced optical Q factor are shown in Fig. 5. The optical Q factor increases as a function of the annealing temperature, suggesting that the quality of the nc-Si film improves with higher annealing temperatures. The values are smaller by a factor of five compared to those measured from a similar c-Si OMC. The effective refractive index of the nc-Si seems to be independent of the annealing temperature and the strain. From the transmission spectra one can obtain the thermo-optical coefficient. A value of $\partial\lambda_r/\partial\Delta T = 0.09$ *nm/K* was measured for a nc-Si OMC [1], and using this value the shift of optical absorption can be translated to the temperature of the cavity. The temperature increase of the cavity per photon is shown in Fig. 6. The temperature increase is much larger than in c-Si, suggesting that the optical absorption is very efficient and the thermal conductance of the nc-Si beam is smaller than that of c-Si beams.

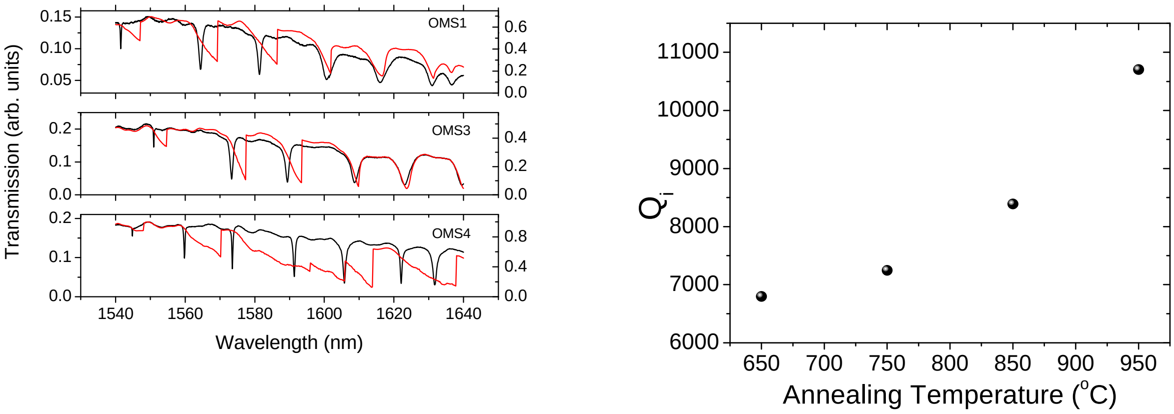

Fig. 5. *(Left) Optical transmission spectra at low and high intracavity photon number (black and red curves respectively). (Right) Optical Q-factor as a function of the annealing temperature.*

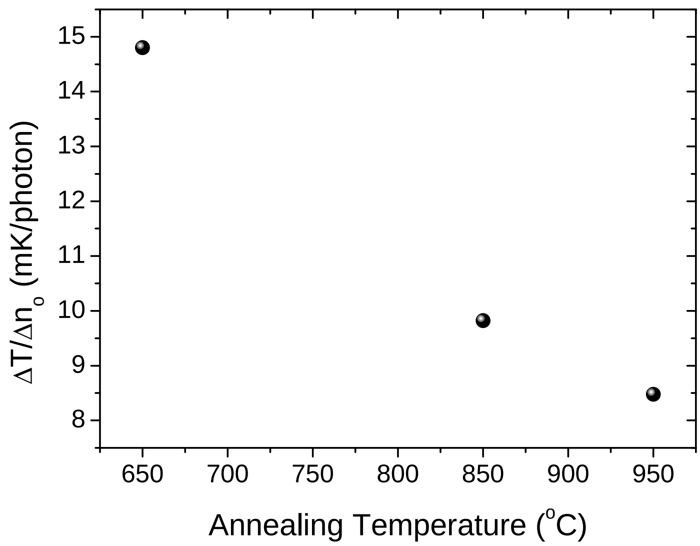

Fig. 6. *Effective temperature increase of the cavity per photon as a function of the annealing temperature of the nc-Si film.*

The **mechanical** modes of a sample annealed at 950 °C are shown in Fig. 7. The low frequency modes, below 1 GHz, are extended modes and the high frequency modes at around 2.45 GHz are localised. The mechanical Q factor as a function of annealing temperature and tensile stress is shown in Fig. 8. The Q factor increases as the annealing temperature increases, suggesting that the improved crystallinity also improves the mechanical Q factor. What is very interesting here is that the mechanical Q factor of OMCs made of nc-Si is higher than the Q factor of devices made of c-Si.

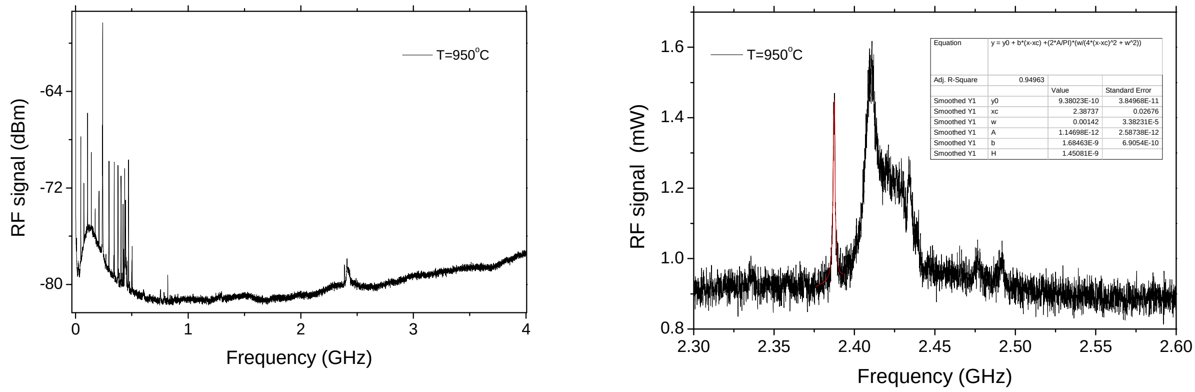

Fig. 7. *(Left) RF spectrum of an OMC made of nc-Si annealed at 950 C. (Right) Zoom of the spectrum around 2.45 GHz.*

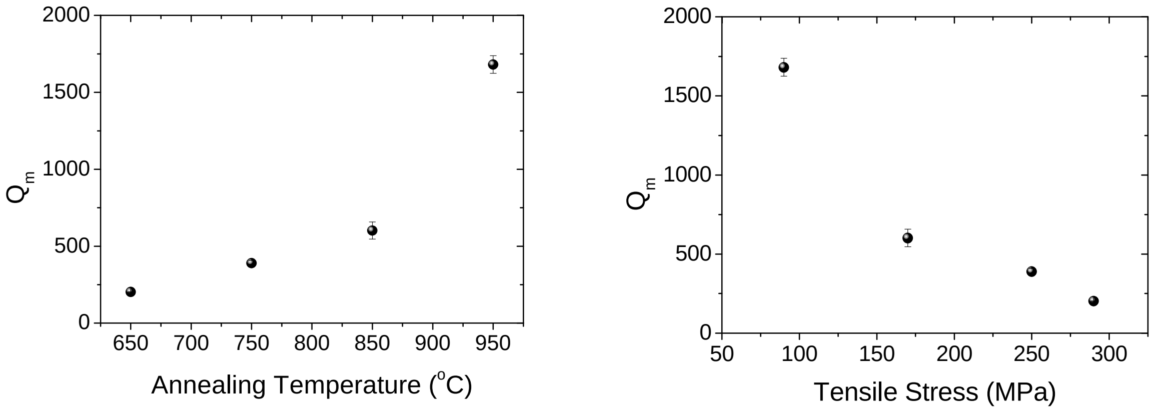

Fig. 8. *(Left) Mechanical Q-factor as a function of the annealing temperature of the nc-Si film. (Right) Mechanical Q factor as a function of the tensile stress.*

FEM simulations of the effect of strain

The effect of strain was studied also using FEM simulations at VTT. The dimensions of the simulated structures are slightly different in comparison to those of the fabricated samples. The target frequency of localised mechanical modes in the simulations was around 2 GHz. The simulated structure is shown in Fig. 9. The beam material is isotropic silicon. The length of a single cell (in x-direction) is 500 nm, the stub width (in x-direction) is 250 nm, the stub length (in y-direction) is 400 nm, the beam width (in y-direction) is 500 nm and the hole diameter is 300 nm. The beam thickness is 220 nm. To take the fabrication imperfections into account, the stub roots are rounded. There are 10 cells and the total length of the beam is 9250 nm, excluding the perfectly matched layer (PML) regions at both ends. PML regions at the end are 1000 nm long. They strongly attenuate the acoustic wave, mimicking a semi-infinite beam and there are no reflections at the artificial boundary where the model is truncated. Damping in the material is not included in the model.

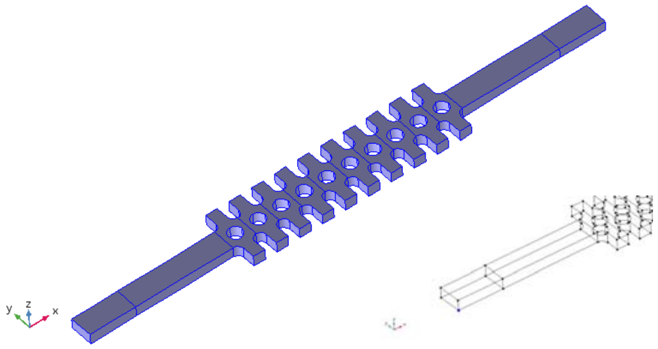

Fig. 9. *Geometry of a 3D nanobeam model. The inset displays one of the two points where y- and z-displacements are set to vanish.*

The simulations reveal that the behaviour of the localised and extended modes is different. The frequency of the localised modes decreases and the frequency of the extended modes increases as a function of the tensile strain. The results of the MHz and GHz range frequencies are given in the Tables 3 and 4. The behaviour of the extended modes can be understood by the increased stiffness of the material. The frequency of the localised modes depends on the coupling of the stubs to the beam and the tensile strain decreases locally the coupling, leading to decrease of the mode frequency.

Table 3. *Effect of strain on extended modes at MHz frequency range.*

No prestress (MHz)	200 MPa prestress (MHz)	400 MPa prestress (MHz)
125.35	131.14	136.48
137.21	137.51	138.06
139.16	141.42	143.68
162.75	163.44	164.35

Table 4. *Effect of strain on localised modes around 2 GHz frequency range.*

No prestress (MHz)	200 MPa prestress (MHz)	400 MPa prestress (MHz)
1902.50	1886.88	1885.56
2012.08	1979.76	1979.41
2069.36	2039.93	2039.77
2071.31	2057.19	2055.61
2166.22	2144.08	2144.33
2205.65	2195.56	2197.18

5. Conclusion

It has been shown in Ref. [1] that the stronger non-linearity of nanocrystalline silicon compared to crystalline silicon is beneficial to self-pulsing and detuning of optomechanical cavities. Here, the effect of tensile strain on the properties of one-dimensional nc-Si optomechanical cavities was investigated. The results show that the crystalline quality of the nc-Si films plays a more important role both in the optical and mechanical properties than the strain. The crystalline quality of polycrystalline material increases as a function of annealing temperature and time, and this trend was observed in the experiments. The tensile stress ranged from a few tens to a few hundreds of MPa, which is still a relatively low value, and the potential effects were obstructed by the stronger impact of the modification of the crystallinity. Thus, it is not possible to distinguish the effect arising from the strain from the effect of the crystalline quality based on these experiments. However, the mechanical Q factor of the nc-Si OMCs is higher at room temperature than the Q factor of c-Si samples. This, together with the enhanced flexibility in the design, e.g., optimising the layer thickness and layer sequence, and in the fabrication demonstrates that nc-Si SOI-like substrates provide an interesting platform to optomechanics technology.

6. Recommendations

To fully understand the behaviour of the nc-Si as OM material, detailed structural characterisation is required. This should include TEM, XRD and AFM measurements. Also, picoacoustic measurements can give detailed information of the refractive index, optical absorption and mechanical damping. The role of the grain boundaries and gap states in the enhanced optical absorption and carrier relaxation, i.e., the Shockley-Read-Hall mechanism, on the optomechanical properties has to be investigated in detail, both experimentally and theoretically. The tentative outcome is a thorough article in a high impact journal to advocate the potential of nanocrystalline silicon in optomechanics.

7. References

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