Materials Science Forum
ISSN: 1662-9752, Vol. 1089, pp 57-61
doi:10.4028/p-3g82bg
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Submitted: 2022-09-03
Revised: 2022-10-28
Accepted: 2022-11-25
Online: 2023-05-26

Correlation between Q-Factor and Residual Stress in Epitaxial 3C-SiC Double-Clamped Beam Resonators

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Keywords: 3C-SiC, MEMS, Q-factor, residual stress

Abstract. In this work, we investigate the correlation between tensile residual stress and Q-factor of double-clamped beams fabricated on epitaxial 3C-SiC layers grown on both <100> and <111> silicon substrates, using a completely optical measurement setup to measure the Q-factor of the resonators and the residual stress of the layers by means of purposely designed micromachined test structures. From the measurements, a clear correlation appears between the residual stress of the SiC layer and the Q-factor of the resonators, with Q-factor values above half a million for resonators fabricated on <111> substrates, showing residual stress around 1 GPa.

Introduction

Q-factor is an important parameter for the performance of a sensor based on mechanical resonance because it is strictly correlated with the resolution of the measurement that can be performed by means of the variation of the resonance frequency of the resonator when it is operated in closed loop [1-3]. In order to obtain a high value of the Q-factor and consequently a high resolution in the measurement, several conditions must be met both by the design of the resonant microstructure and by the material used to build them. For Double Clamped (DC) beams, a popular geometry for resonant sensing of various types, the design of thin beams is necessary to achieve high Q-factors in the thermoelastic-limited regime, which corresponds to the vacuum operation of the resonators. Moreover, the presence of highly tensile residual stress in the layer used to fabricate the DC beams was reported to be beneficial for the Q-factor for its possible effects of reduction of the damping on the beam anchors during vibration. Following this route, exceptionally high values of Young's modulus were reported on high-stress 3C-SiC layers grown on <111> silicon substrates by Atomic Layer Deposition [4]. In this paper, the correlation between residual stress and Q-factor of DC beams manufactured by 3C-SiC layers obtained by hetero-epitaxy on both <100> and <111> Si substrates, showing different levels of tensile residual stress, is investigated.

Fabrication

The double-clamped beams were fabricated using 3C-SiC layers grown on <111> and <100> Si substrates, in a horizontal, low pressure, resistively heated hot wall Chemical Vapor Deposition (CVD) system with rotating sample holder [5]. Hetero-epitaxial 3C-SiC growth on Si substrates was achieved using a classical two-step process with purified hydrogen (H_2)/argon (Ar) mix as carrier gas, silane (SiH_4) and propane (C_3H_8) as Si- and C-precursors [6]. N-type doping with nitrogen was obtained by introducing N_2 to reactor chamber. The fabrication process flow already reported in [7] was adopted to fabricate the SiC DC beams by front-side micromachining of the grown layers.

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Optical Measurements

Residual stress and Q-factor measurements were performed using an optical experimental setup (Fig. 1) in which a green laser diode (L515A1 of Thorlabs) was used to induce the vibration of the beam by sinusoidal voltage at different frequencies, while a Doppler vibrometer was employed to measure the beam vibration, to measure the resonance frequency of the resonator. Fig. 2 shows a double-clamped beam during the optical measurement: the green laser (λ = 515 nm) provides the bias, while the red laser (λ = 633 nm) is used by the head sensor of the Doppler vibrometer for sensing.

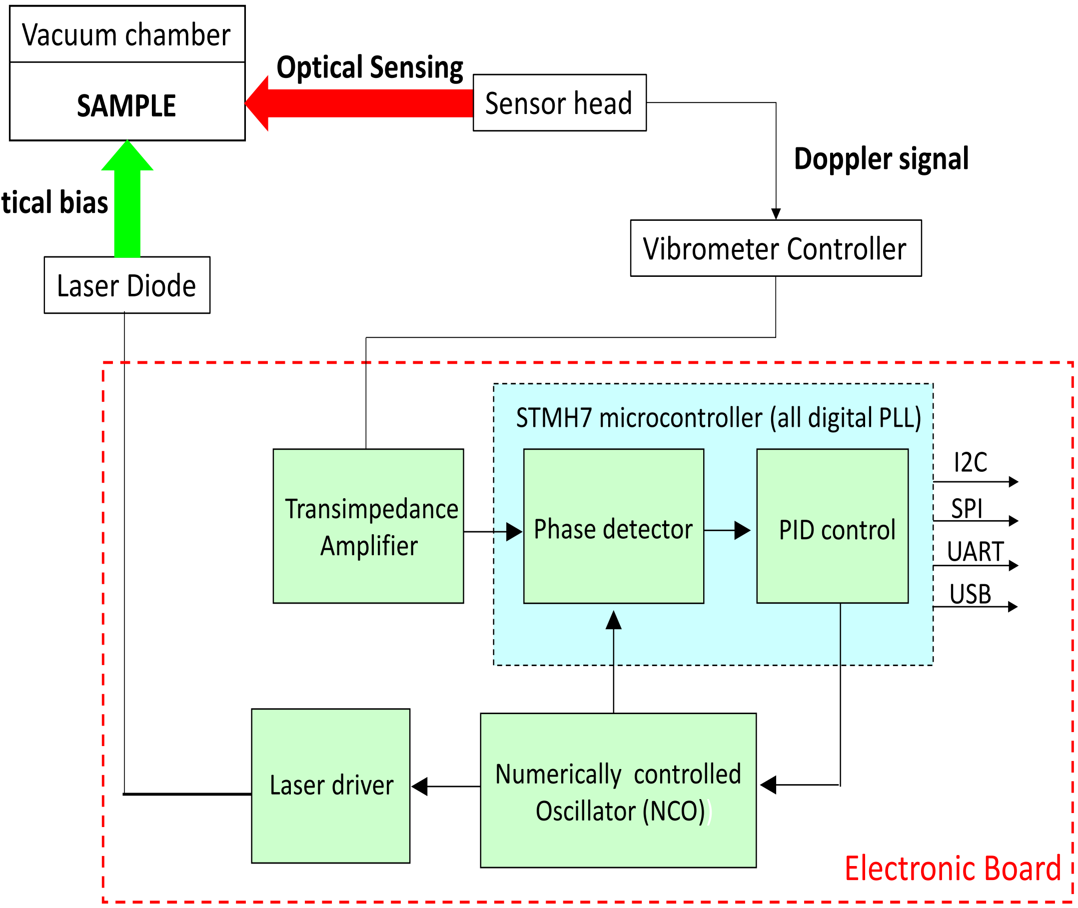

Fig. 1. Block scheme of the optical setup used for the Q-factor measurements on the DC beams.

In this way, the Residual Stress can be easily obtained with the following formula [8]:

$$f_r = \frac{1}{2L}\sqrt{\frac{\sigma}{\rho}} \qquad (1)$$

where f_r is the resonance frequency, L the beam length, ρ the density (assumed as 3210 kg/m^3) and σ the residual stress.

A custom electronic readout was used to produce the actuation signal controlling the laser diode over a range of frequencies centered on the resonance of the beam and analyze the output of the doppler vibrometer, calculating the Q-factor of the beams by estimating the Full Width Half Maximum (FWHM) of the resonance peak at -3 dB (Fig. 3), according to the formula:

$$Q = \frac{f_r}{\Delta f} \qquad (2)$$

where Δf is the FWHM.

The electronic readout used had a minimum frequency variation of 0.07 Hz, which allowed to measure high Q-factor values in the frequency range where the resonance of the DC beam appears. In the frequency sweep, a hold time of 500 msec was maintained on each frequency point to assure a good stabilization of the beam vibration from one point to another.

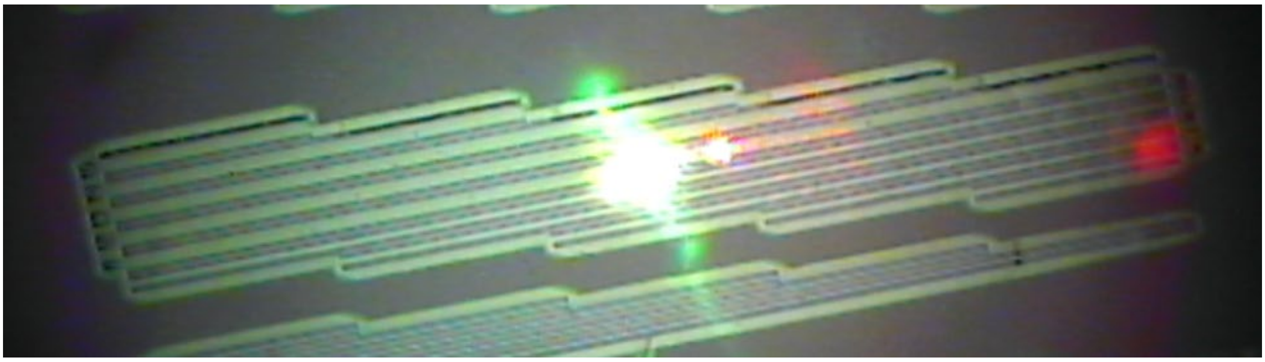

Fig. 2. Double-clamped beam during optical measurement. The green and red lasers are focused on the beam for actuation and sensing of the beam vibration.

The samples under measurement were contained in a vacuum chamber equipped with a transparent window to allow the optical Q-factor measurements at a vacuum level around 10^{-7} Bar.

The double-clamped beams under measurement had a length of 1000 μm and width of 16 μm, while the thickness depended on the specific 3C-SiC layer characterized. The Q-factor measurements were correlated with residual stress measurements performed on the same samples using the method already reported in [7]. From the results obtained, summarized in Tab. 1, the correlation between the Q-factor of the beams and the tensile stress of the layers was confirmed, since the Q-factor of the SiC beams realized on the <111> substrates was always significantly higher than the one obtained on the beams fabricated with the <100> layers, a result which well correlates with the much higher tensile stress measured on the former substrates. Another interesting observation was that a high Q-factor (sometimes above half a million) was obtained also on relatively thick epitaxial 3C-SiC resonators (thickness in the order of 1 μm), as shown in Fig. 4.

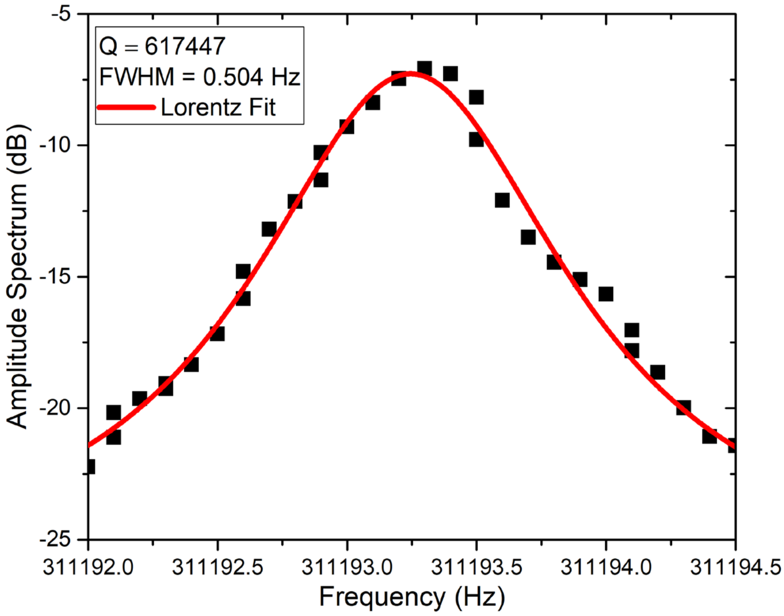

Fig. 3. Amplitude spectrum of <111> double-clamped beam resonator (W1) around resonance frequency.

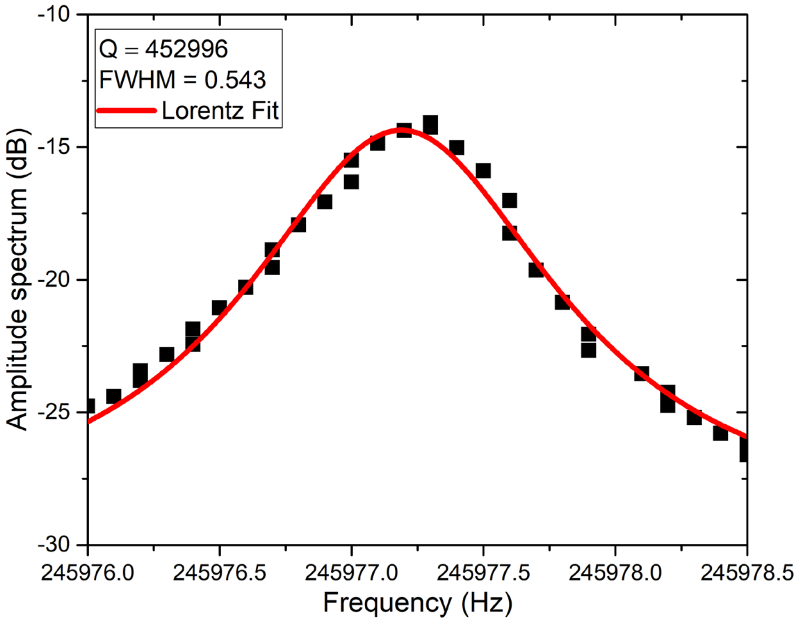

Fig. 4. Amplitude spectrum of <100> double-clamped beam resonator (S3) around resonance frequency.

Table 1. Comparison of Q-factor and Residual Stress values of 3C-SiC samples.

Sample Id	Si substrate	Doping	3C-SiC Layer Thickness (μm)	Q-Factor	Residual Stress (MPa)
W1	<111>	NID[1]	0.89	617447	1010
W2	<111>	NID[1]	0.73	636150	982
W7	<111>	NID[1]	0.61	431043	738
S1	<100>	N^+	0.8	344425	207
S2	<100>	NID[1]	0.8	306729	242
S3	<100>	NID[1]	1.1	452996	274

[1] Non-Intentionally Doped

Summary

The correlation between tensile residual stress and Q-factor of Double-Clamped (DC) beams was investigated. The DC beams were fabricated on epitaxial 3C-SiC layers grown on both <100> and <111> silicon substrates. An optical experimental setup with a custom electronic readout system was used to perform resonance frequency measurements and Q-factor estimation. Thanks to the high resolution of the electronic board, it was possible to measure high Q-factor value of the resonator due to the high tensile stress of the layer. The results confirmed the correlation between Q-factor and residual stress and showed how a half million Q-factor could be obtained on relatively thick 3C-SiC layers.

Funding

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 863220.

Acknowledgments

The contribution of Mr. Filippo Bonafè, Mr. Fabrizio Tamarri, and Mr. Michele Sanmartin in the clean room processing of the samples is acknowledged.

References

[1] L. Belsito, M. Ferri, F. Mancarella, A. Roncaglia, J. Yan, A. A. Seshia and K. Soga, The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers & Eurosensor XXVII), Barcelona, 992-995 (2013).

[2] L. Belsito, M. Ferri, F. Mancarella, L. Masini, J. Yan, A. A. Seshia, K. Soga, A. Roncaglia, Sens. Actuat. A: Physical, 239, 90-101 (2016).

[3] L. Belsito, M. Bosi, F. Mancarella, M. Ferri, A. Roncaglia, J. Microelectromech. Syst., 29, 117-128 (2020).

[4] A. R. Kermany, G. Brawley, N. Mishra et al., Appl. Phys. Lett., 104(8), 81901 (2014).

[5] A. Leycuras, Materials Science Forum, 338, 241-244 (2000).

[6] M. Zielinski, S. Monnoye, H. Mank, C. Moisson, T. Chassagne, A. Michon, M. Portail, Mater. Sci. Forum, 924, 306 (2018).

[7] S. Sapienza, L. Belsito, D. Marini et al., Micromachines, 12, 1072 (2021).

[8] S. Verbridge, J. M. Parpia, R. B. Reichenbach, L. M. Bellan, H. G. Craighead, J. Appl. Phys., 99(12), 124304 (2006).