Key Engineering Materials
ISSN: 1662-9795, Vol. 984, pp 29-33
doi:10.4028/p-50UjDn

Submitted: 2023-09-07
Revised: 2024-05-16
Accepted: 2024-05-20
Online: 2024-08-22

Fabrication of Wafer-Level Vacuum-Packaged 3C-SiC Resonant Microstructures Grown on <111> and <100> Silicon

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Keywords: 3C-SiC, MEMS resonators, Q-factor, vacuum encapsulation, Ti getter

Abstract. In this work, the fabrication of wafer-level vacuum packaged 3C-SiC resonators obtained from layers grown on <100> and <111> silicon is reported. The resonant microstructures are double-clamped beams encapsulated by glass-silicon anodic bonding using titanium-based vacuum gettering. Open-loop resonance frequency measurements are performed on the vacuum-packaged devices showing Q-factor values up to 292,000 for <100> and 331,000 for <111> substrates, with a maximum vacuum level around 10^{-2} mbar inside the encapsulations with Ti getter.

Introduction

The cubic silicon carbide (3C-SiC) is an emerging material for MEMS thanks to its outstanding mechanical properties. For mechanical resonators, in particular, the high Young's modulus and tensile residual stress obtained by growing silicon carbide (SiC) on silicon (Si) [1] provide the possibility to achieve a high quality factor (Q-factor), which is an important parameter for the performance of a sensor based on mechanical resonance variation, such as a resonant strain sensor [2-4], because it is strictly correlated with the measurement resolution. Another important aspect for the fabrication of a strain sensor is the vacuum packaging of the resonators, which is necessary to achieve a high Q-factor without the aid of an external vacuum pump.

In this paper, we present a technology for fabricating wafer-level vacuum-packaged 3C-SiC resonators with high Q-factor on both <100> and <111> Si substrates, which can be used as resonant strain sensors. The technology is based on glass-silicon anodic bonding and employs Titanium (Ti) layers for vacuum gettering inside the encapsulation. We propose a comparison between the process yield and the characteristics of the resonators obtained on the two types of substrates, in which 3C-SiC layers with very different residual stress levels are obtained.

Fabrication

Two hetero-epitaxial non-intentionally doped 0.8 μm and 0.6 μm thick 3C-SiC thin films were grown on 500 μm and 1 mm thick <100> and <111> p-type silicon substrates using Chemical Vapor Deposition with a rotating sample holder [5]. Fig. 1 shows the process flow adopted to fabricate wafer-level vacuum packaged 3C-SiC resonators. After SiC growth, a mask composed of two stacked silicon dioxide (SiO_2) (2 μm thick) and polycrystalline silicon (300 nm thick) layers was used to etch the SiC layer grown on silicon (step 7 in Fig. 1). Then, another SiO_2 mask was exploited to protect the SiC layer during the release step performed by isotropic silicon plasma etching (step 10). On a separate borosilicate glass substrate, wet etching using a chrome(Cr)/gold(Au) mask was used to produce 100 μm deep cavities for the encapsulation (step 15). In some of them, a 1 μm thick Ti layer was inserted for vacuum gettering [6] using either lithography and wet etching or shadow masking, in different dies on the wafer (step 17). The glass and Si wafers were bonded anodically at 400°C after a 2 h degassing in high vacuum (step 18) to encapsulate the resonators.

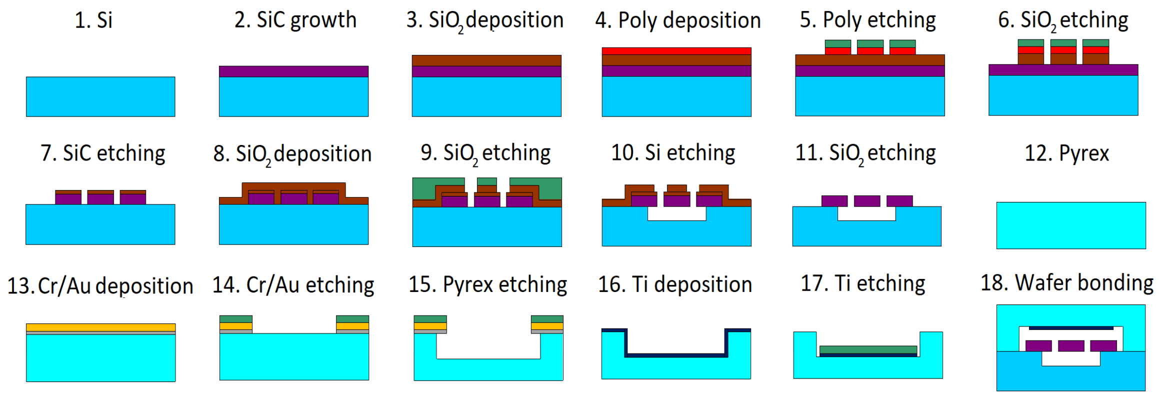


Fig. 1. Process flow adopted for fabrication of the wafer-level vacuum-packaged 3C-SiC resonant microstructures.

An optical experimental setup was used to perform Q-factor measurements on double-clamped beams with length of 900 µm and width of 24 µm inside the encapsulations, exploiting the transparency of the glass substrate. The measurements were performed by inducing the vibration of the beams with a pulsed laser operated at variable frequency and using a Doppler vibrometer to measure the beam vibration at resonance, as described in [7]. Fig. 2 shows a picture taken at the optical microscope of the vacuum packaged resonator devices after anodic bonding, in which resonators with different lengths are shown.

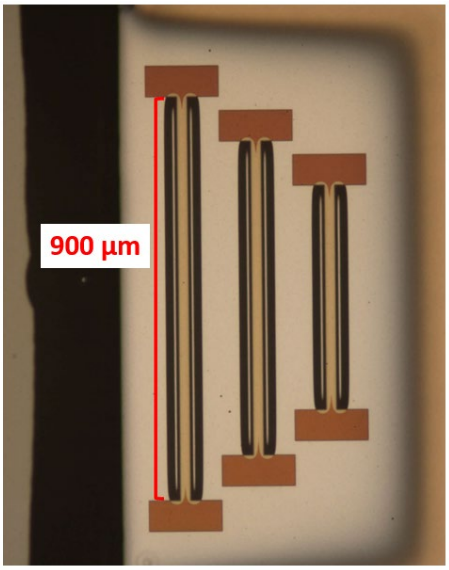
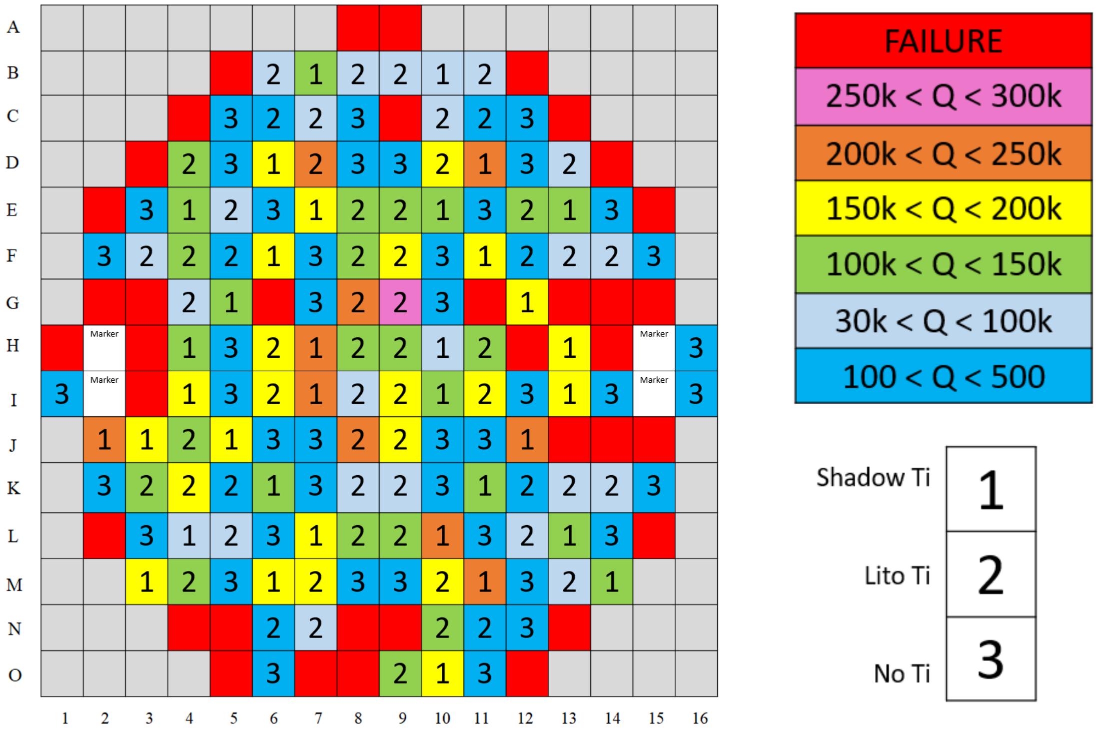


Fig. 2. Vacuum-packaged microstructures on <100> substrate after anodic bonding.

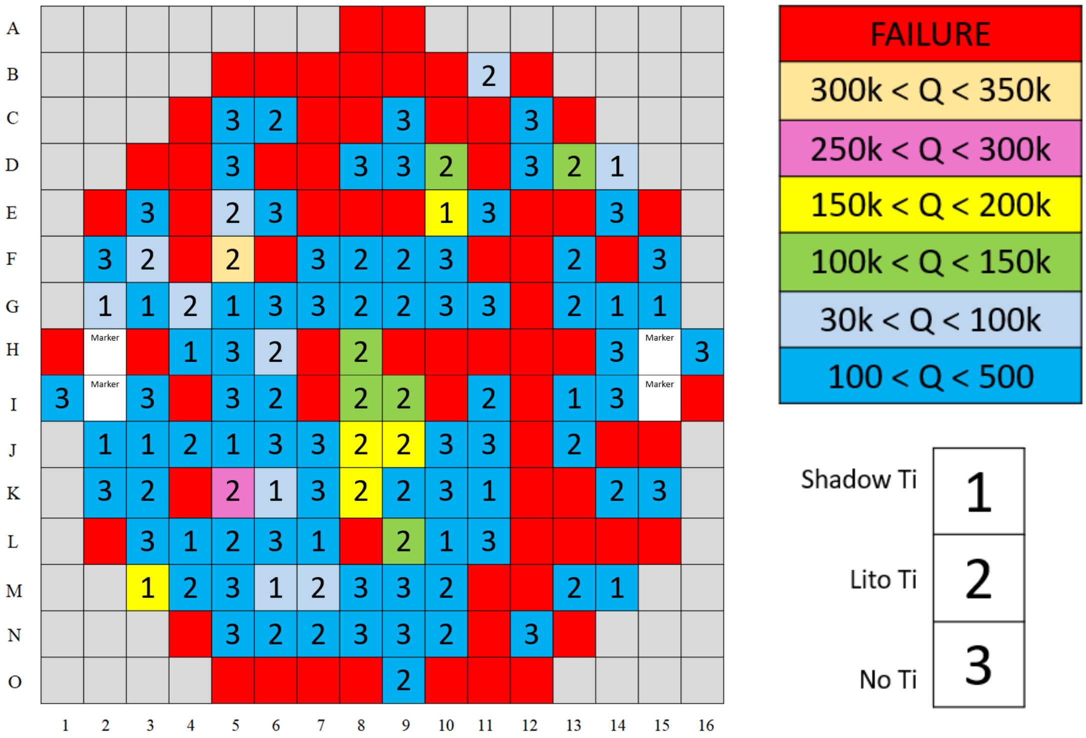
Results

Figs. 3 and 4 show the Q-factor measurements performed on vacuum-encapsulated double-clamped beams on a <100> and <111> wafer, respectively. The legend describes the presence of Ti getter inside the cavities and the different range of Q-factor values, expressed in colour scale. The process yield is also highlighted by reporting in red the dies, in which the resonators were not measurable because of a failure.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A								🟥	🟥							
B					🟥	2	1	2	2	1	2	🟥				
C				🟥	3	2	2	3	🟥	2	2	3	🟥			
D			🟥	2	3	1	2	3	3	2	1	3	2	🟥		
E		🟥	3	1	2	3	1	2	2	1	3	2	1	3	🟥	
F		3	2	2	2	1	3	2	2	3	1	2	2	2	3	
G		🟥	🟥	2	1	🟥	3	2	2	3	🟥	1	🟥	🟥	🟥	
H	🟥	Marker	🟥	1	3	2	1	2	2	1	2	🟥	1	🟥	Marker	3
I	3	Marker	🟥	1	3	2	1	2	2	1	2	3	1	3	Marker	3
J		1	1	2	1	3	3	2	2	3	3	1	🟥	🟥	🟥	
K		3	2	2	2	1	3	2	2	3	1	2	2	2	3	
L		🟥	3	1	2	3	1	2	2	1	3	2	1	3	🟥	
M			1	2	3	1	2	3	3	2	1	3	2	1		
N				🟥	🟥	2	2	🟥	🟥	2	2	3	🟥			
O					🟥	3	🟥	🟥	2	1	3	🟥				

Fig.3. Results of Q-factor measurements on encapsulated double-clamped beam resonators on <100> wafer.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A								🟥	🟥							
B					🟥	🟥	🟥	🟥	🟥	🟥	2	🟥				
C				🟥	3	2	🟥	🟥	3	🟥	🟥	3	🟥			
D			🟥	🟥	3	🟥	🟥	3	3	2	🟥	3	2	1		
E		🟥	3	🟥	2	3	🟥	🟥	🟥	1	3	🟥	🟥	3	🟥	
F		3	2	🟥	2	🟥	3	2	2	3	🟥	🟥	2	🟥	3	
G		1	1	2	1	3	3	2	2	3	3	🟥	2	1	1	
H	🟥	Marker	🟥	1	3	2	🟥	2	🟥	🟥	🟥	🟥	🟥	3	Marker	3
I	3	Marker	3	🟥	3	2	🟥	2	2	🟥	2	🟥	1	3	Marker	🟥
J		1	1	2	1	3	3	2	2	3	3	🟥	2	🟥	🟥	
K		3	2	🟥	2	1	3	2	2	3	1	🟥	🟥	2	3	
L		🟥	3	1	2	3	1	🟥	2	1	3	🟥	🟥	🟥	🟥	
M			1	2	3	1	2	3	3	2	🟥	🟥	2	1		
N				🟥	3	2	2	3	3	2	🟥	3	🟥			
O					🟥	🟥	🟥	🟥	2	🟥	🟥	🟥				

Fig.4. Results of Q-factor measurements on encapsulated double-clamped beam resonators on <111> wafer.

The first difference that appears evident from the reported results is the significantly lower yield obtained on the <111> substrate where a larger number of red-marked dies are present in the map. The reason for these more frequent failures was evident from the microscope inspection of the samples through the glass encapsulation after bonding. Some cracks appear on the SiC, due to the much higher residual stress of the 3C-SiC layer grown on <111> silicon (around 1 GPa [1]), which sometimes produce a failure on the resonators. These cracks were clearly visible at the microscope.

On the <100> substrates, on the contrary, the residual stress is much lower (around 300 MPa [1]) and consequently no cracks appear, enabling a higher yield of the fabrication.

The cracks observed on the <111> substrate also explain the presence of a larger number of devices with low Q-factor, in the map reported in Fig. 4. Indeed, often the cracks also propagate within the Si substrate, producing a failure of the vacuum encapsulation, so many <111> devices are operating in air, with a Q-factor around 100. This is not the case for the <100> devices. Overall, the process yield obtained was 80% for the <100> and 60% for the <111> substrate, whereas the percentage of resonators with Q-factor larger than 100,000 was 44% and 12% for the <100> and <111> devices, respectively.

Another important datum was the effect of Ti getter inside the encapsulations, which proved to have a very important effect on the vacuum level, as can be deduced by the average Q-factor values measured on devices encapsulated with and without Ti getter layer in the encapsulation (Fig. 5). This is true for both substrates, whereas the average Q-factor is higher on the <100> devices because of cracks on vacuum failure. The average Q-factor of devices with vacuum encapsulation including Ti getter layers produced by lithography and shadow mask is also reported in the plot, showing however little difference on both types of substrates.

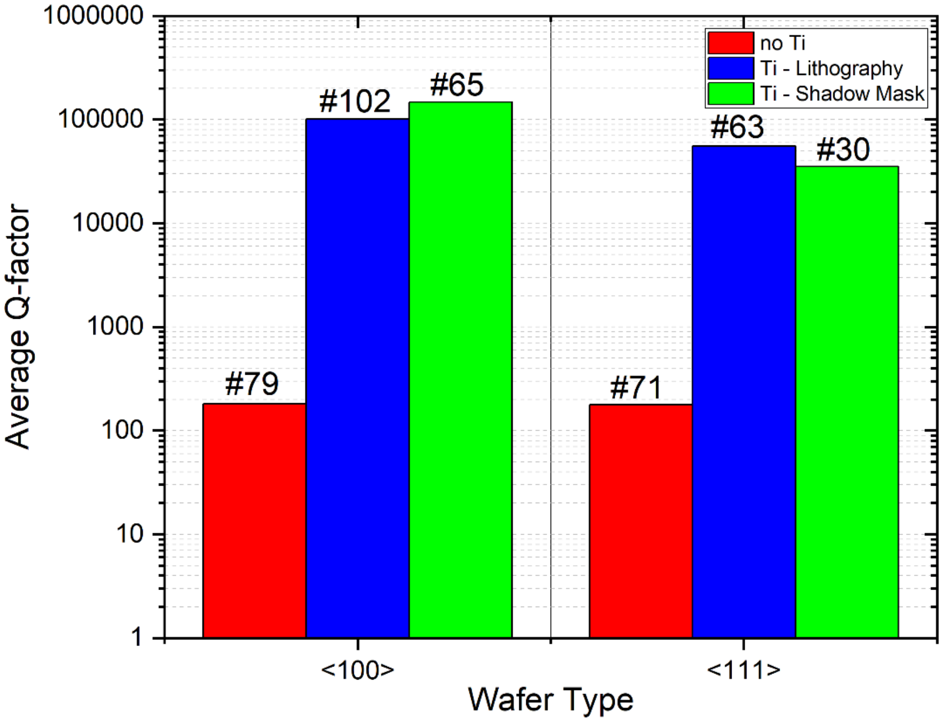


Fig.5. Average Q-factor measurements on <100> and <111> wafers. The label above the bar reports the number of measured structures.

On the fabricated resonators, the geometry of the encapsulation was also varied. The effect of the encapsulation geometry on the resonator Q-factor was already reported in [8] and will not be repeated here.

A conclusive remark can be made on the peak Q-factors measured on the two substrates, which were 292,000 and 331,000 for the <100> and <111> substrates, respectively. The higher maximum Q-factor observed on the <111> resonators is probably related to the different thermoelastic damping and residual stress properties of this material [7] and not to a different vacuum level of the encapsulation.

Summary

In this work, a technology for fabricating wafer-level vacuum-packaged SiC resonators have been described. To obtain high vacuum level and consequently high Q-factor values on the resonators, a getter layer made of titanium was inserted on the borosilicate glass encapsulation obtained with anodic bonding technique on the 3C-SiC on Si wafer. The presence of such getter layer proved to be essential to obtain a high enough vacuum level inside the cavities and consequently a high Q-factor on the resonators. With the technology presented, Q-factors up to 292,000 and 331,000 on resonators manufactured from <100> and <111> 3C-SiC layers, respectively, were obtained.

Funding

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

Acknowledgements

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

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