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Two-Port Piezoelectric Silicon Carbide MEMS Cantilever Resonator

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Abstract: A two-port silicon carbide single-clamped beam (cantilever) microelectromechanical system (MEMS) resonant device actuated piezoelectrically and sensed piezoelectrically has been designed, fabricated and tested. Lead zirconium titanate (PZT) has been used as active material to implement the piezoelectric actuator and sensor. Piezoelectric electrodes have been placed on the top of the single 3C-SiC beam forming a flexural-mode resonator. Operation has been demonstrated with two-port measurements of the transmission frequency response. The 250-μm long device resonates at 371 kHz with Q factor of 385 in atmospheric conditions. The tuning of the resonant frequency has been demonstrated by applying DC bias voltage in the range 0 V – 10 V and frequency tuning range of 1025 ppm has been achieved.

Key words: Silicon carbide, MEMS, resonator, cantilever, piezoelectric actuation, piezoelectric sensing, frequency tuning

Dvovhodni piezoelektrični MEMS resonator na ročico iz silicijevega karbida

Povzetek: Načrtovan, izdelan in testiran je bil, piezoelektrično vzbujan in merjen, dvovhodni mikroelektromehanski (MEMS) resonatorski sistem z ročko. Za aktuator in senzor je bil uporabljen svinčev cirkonijev titanat (PZT). Piezoelektrične elektrode so nameščene na vrh enojne 3C-SiC gredi, ki tvori upogibni resonator. Delovanje je demonstrirano z dvovhodnimi meritvami prenosa odzivne frekvence. pod atmosferskimi pogoji 250-μm dolg element resonira s frekvenco 371 kHz in Q faktorjem 385. Uglaševanje resonančne frekvence je predstavljeno s spreminjanjem DC napetosti od 0 – 10 V, pri čemer je bilo območje uglaševanja frekvence doseglo 1025 ppm.

Ključne besede: silicijev karbid, MEMS, resonator, ročica, piezoelektrično vzbujanje, piezoelektrični senzor, uglaševanje frekvence

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1. Introduction

Microelectromechanical system (MEMS) resonant devices are being increasingly considered for replacing filter [1] components and quartz crystal [2] currently used in communication systems. Relatively small dimensions and low operating voltages enable MEMS resonators to solve power consumption and miniaturisation issues in portable wireless devices [2, 3]. Selection of the material plays a very important role for realization of high efficiency MEMS resonant devices. Silicon carbide (SiC), a wide band-gap semiconductor, possesses outstanding mechanical properties that make SiC the most promising material for MEMS resonator applications [4]. SiC exhibits a large Young's modulus to mass density ratio and the resonant frequency of a SiC resonator can be three times higher than its silicon (Si) equivalent [5]. 3C-SiC has emerged as the dominant polytype for MEMS applications as it can be synthesised on Si wafers, potentially leading to large-scale production. Other polytypes such as 4H-SiC and 6H-SiC form at temperatures above the melting point of Si [4].

Electrical actuation and sensing of resonator mechanical vibration is essential requirement for the practical implementation of MEMS resonators. Electrostatic and piezoelectric transductions have emerged as the leading techniques and both have been widely implemented in Si and SiO_2 resonators [3,6]. However, the complex fabrication process in electrostatic transduction associated with achieving an electrode-to-resonator gap spacing in the nanometric scale motivates the use of piezoelectric transduction. Recently, 3C-SiC has been integrated with lead-zirconium-titanate (PZT) ports allowing electrical actuation [7] and sensing [8-10] of flexural-mode 3C-SiC resonators.

The overall structural design plays an important role in achieving expected performance of flexural-mode resonators. Even though single-clamped beam (cantilever) resonators exhibit a resonant frequency about 6 times lower than double-clamped beam (bridge) and about 10 times lower than circular membrane (ring) resonators [11], they are characterized by the largest vibration amplitude, which is essential for piezoelectric sensing of the vertical resonant vibration. In this paper, piezoelectric sensing of a 3C-SiC cantilever resonator that is actuated piezoelectrically has been presented. The device has been designed as a two-port single-clamped vertical-mode beam resonator with a top piezoelectric actuator (input-port) and a sensor (output-port) made of platinum (Pt) and PZT (Figure 1). The resonant frequency has been determined by two-port measurements of the resonator's transmission frequency response. In addition, resonant frequency tuning has been demonstrated by applying DC bias voltages.

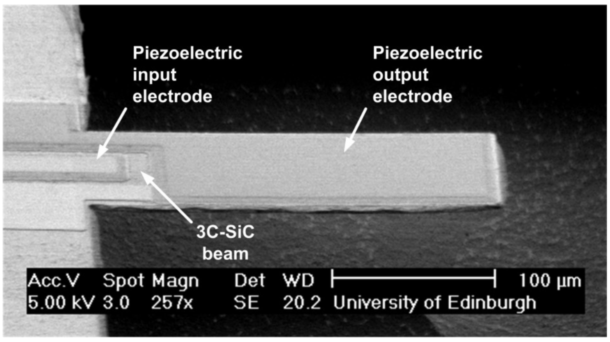

Figure 1: Scanning electron micrograph of the fabricated 3C-SiC single-clamped beam (cantilever) resonant device with input and output piezoelectric electrodes placed on the top of the beam.

2. Piezoelectric transduction and device operation

Piezoelectric effect refers to the property of a material to become electrically polarized when subjected to mechanical stress and conversely, to mechanically deform under application of electric field. Piezoelectricity can be used as a transduction technique for electrically inducing (actuating) or detecting (sensing) a mechanical deformation of a structure. The structure of the presented device consists of two dominant layers, a piezoelectric layer positioned on the top of an elastic 3C-SiC layer. The shape of the 3C-SiC layer is the single-clamped beam (i.e. cantilever). When an electric field is applied to the actuating piezoelectric layer (input electrode) of the device, the induced expansion/compression of the piezoelectric layer results in a shear stress that is transformed in bending moment, and consequently the beam deflects in the vertical direction. If an alternating electric field is applied with a frequency matching the structure's natural frequency, the resonator's active body (beam) is driven into resonance.

Due to the reciprocity of the piezoelectric effect, the beam deflection in the vertical direction can be sensed by detecting the voltage difference as a result of the change in the electric field induced by the mechanical strain. In particular, when the resonator's beam is vibrating, an oscillating voltage with a frequency equal to the frequency of the mechanical oscillations can be detected across the piezoelectric material of the sensing (output) electrode.

3. Experimental details

3.1 Device design

The device has been designed as a two-port single-clamped vertical-mode beam resonator with piezoelectric electrodes placed on the top of the 3C-SiC beam. As the piezoelectric material, lead zirconium titanate (PZT) has been used because of its high piezoelectric coefficient [12]. Platinum (Pt) has been used as top and bottom metal contacts between which PZT has been sandwiched to form the actuating (input) and sensing (output) electrode. The schematic of the designed device together with the beam dimensions is shown in Figure 2. The resonator's beam length is 250 µm and beam width is 100 µm. The input electrode has been designed with a length of 25 µm (1/10 of the beam length) and with a width of 35 µm. The strong electromechanical coupling offered by piezoelectric transduction [6] allows induction of relatively large vibration amplitude by positioning actuation electrode close to the root of the beam, giving the possibility of designing additional sensing electrode on the remaining part of the single beam. In order to maximize the electrical output, the sensing piezoelectric electrode covers most of the surface of the beam.

3.2 Fabrication

The process for the device fabrication starts with a 2 µm thick 3C-SiC epilayer deposition on 4-inch Si wafer [13]. A 100 nm thick silicon dioxide (SiO_2) passivation layer has been grown thermally. On top of the SiO_2, a

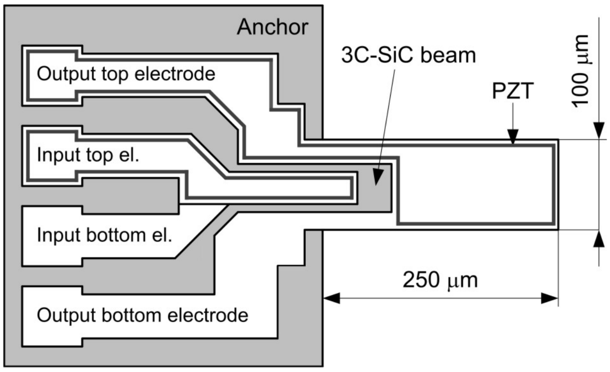

Figure 2: Schematic of the designed device with the beam dimensions.

titanium (Ti) layer (10 nm) has been deposited as an adhesion layer between Pt layer and substrate. The Pt/PZT/Pt stack has been deposited with thicknesses of 100/500/100 nm [14], respectively. Once all layers have been deposited, the electrode stack has been patterned photolithographically. The top Pt and bottom Pt/Ti layers have been dry etched [7] whereas PZT has been wet etched [15]. After depositing a 3 μm thick SiO_2 layer to be used for masking the 3C-SiC layer, the beam shape has been patterned photolithographically and the exposed SiO_2 has been dry etched. The 3C-SiC beam has been plasma etched and released using a SF_6/O_2 gas mixture [16]. Afterwards, the residues of the masking SiO_2 left on the 3C-SiC surface have been removed in a CF_4/H_2 plasma. The detailed fabrication process for the Pt/PZT/Pt/SiC beams has been reported elsewhere [7]. The schematic side view of the fabricated device including the layers thicknesses is shown in Figure 3.

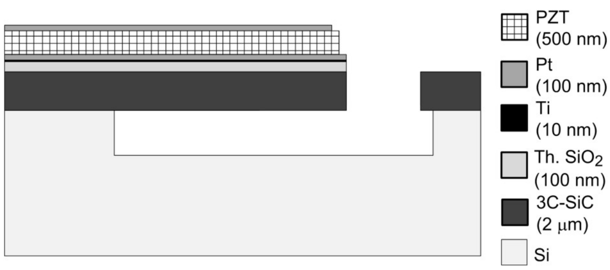

Figure 3: Schematic side view of the fabricated device.

3.3 Measurement setup

Two-port measurements of the fabricated device have been performed with an HP 8753C vector network analyzer. Signal-ground (SG) probes have been used and full two-port calibration (short, open, load, and through - SOLT) has been performed before starting the measurements. The device has been tested without any signal amplification or impedance matching (Figure 4). The bottom electrodes of the device under test have been grounded, while each of the two top electrodes has been used for either piezoelectrical actuation or sensing. In order to perform the tuning of the resonant frequency, the actuating AC signal applied with the network analyzer has been superimposed to a DC signal provided by an external stabilized DC power supply. All measurements have been performed at atmospheric pressure.

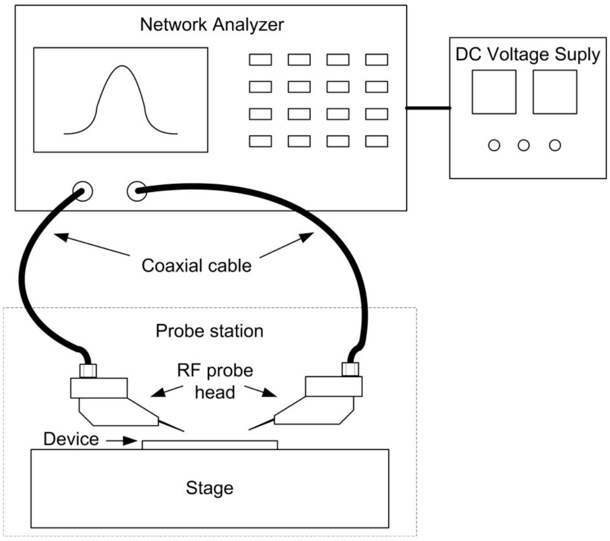

Figure 4: Schematic of the measurement setup.

4. Results and discussion

4.1 Resonant frequency detection

Measured transmission frequency response, both magnitude and phase, of the device is shown in Figure 5. The power of the input signal used has been set at 10 dBm and frequency swept from 367 kHz to 375 kHz. No DC bias voltage has been used for this measurement. The resonant frequency has been measured to be 371.174 kHz. The maximum resolution error of the resonant frequency measurements has been calculated to be 13 ppm. The phase change between output and input signal has been measured to be about 100°. Quality (Q) factor defined as ratio of the resonant frequency and the bandwidth of 3dB transmission magnitude drop has been calculated to be 385. Measurements performed in vacuum should give higher values for the Q factor [17]. Furthermore, the insertion loss should be additionally reduced under appropriate impedance matched conditions between the device input/output and the 50 Ω load impedances of the network analyzer.

4.2 DC voltage tuning

In piezoelectric MEMS resonators such as the device presented in this paper (Figure 1), the piezoelectric effect can be used for driving the structure into reso-

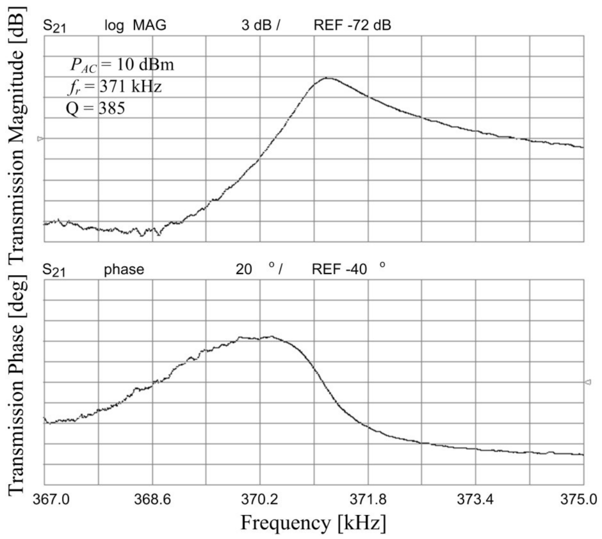

Figure 5: Two-port measurements of the transmission frequency response of the 250 µm-long device.

nance and at the same time for tuning the resonant frequency by applying a superimposed DC bias voltage at the input [18, 10]. Figure 6a shows the transmission magnitude plots for different values of DC bias voltage. A constant input AC signal power of 10 dBm has been applied to the input electrode while the DC bias voltage has been swept in the range 2 V - 8 V with steps of 2 V. The resonant frequency has been shown to increase linearly as the DC bias voltage increases. Figure 6b shows the resonant frequency shift measured at different DC bias voltages with AC input power equal to 10 dBm. As the DC bias increases from 0 V to 10 V, the resonant frequency shift increases by 1025 ppm (i.e. the resonant frequency increases by 380 Hz).

The increase in resonant frequency obtained when increasing the DC bias voltage is attributed to the influence of the electric field on the stress and mass density of the piezoelectric active layer [19, 10]. As the DC bias voltage increases, the stress within the structure induced by the piezoelectric layer increases thus influencing the structure's resonant frequency [10]. Since the resonant frequency is dominated by the 3C-SiC layer and its internal stress, the frequency tuning capability of our device is relatively small comparing to other piezoelectric resonators [18, 20]. Wider frequency tuning can be obtained by increasing the input electrode length [10]. DC bias voltage adjustments can be used to compensate for a frequency shift caused by fabrication processes and operating conditions.

5. Conclusions

The design, fabrication and operation of a novel two-port 3C-SiC cantilever resonant device actuated piezo-

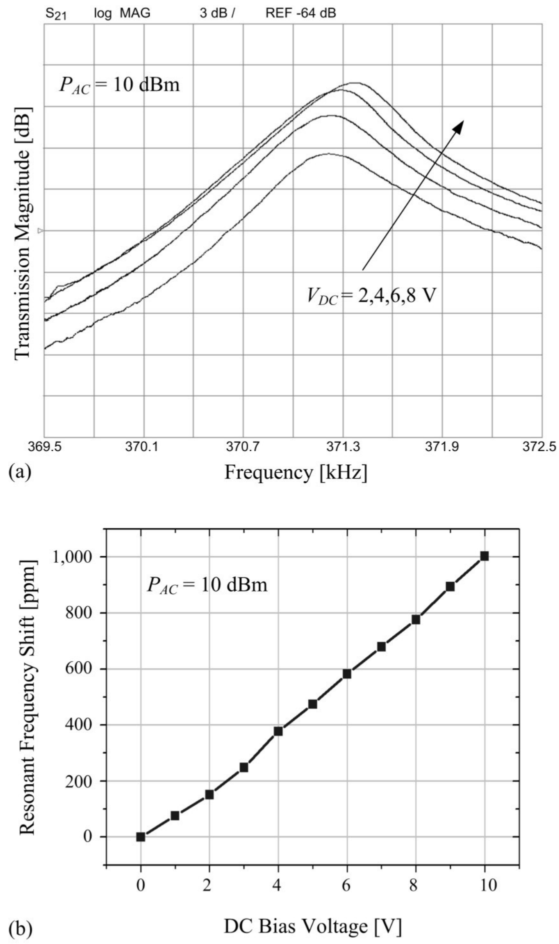

Figure 6: Transmission magnitude plots for different DC voltages (a) and measured resonant frequency shift versus DC bias voltage (b).

electrically and sensed piezoelectrically has been presented. PZT has been used as the piezoelectric material and sandwiched between Pt layers to form transducer electrodes that have been placed on the top of the 3C-SiC beam. From the transmission frequency response measurements, it has been shown that the resonant frequency of the presented device measured at atmospheric pressure is 371 kHz with a Q factor of 385. For the device operation, a DC bias voltage is not required and therefore, the device is suitable for low-power timing and frequency control applications. Resonant frequency tuning range of 1025 ppm is demonstrated by applying DC bias voltages in the range 0 V - 10 V. This tuning method can be used to overcome fabrication tolerances and reliability issues.

Acknowledgments

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References

1. C. S. Lam, "A review of the recent development of MEMS and crystal oscillators and their impacts on the frequency control products industry", IEEE Int. Ultrason. Symp. Proc., pp. 694-704, 2008.
2. C. T.-C. Nguyen, "MEMS Technology for Timing and Frequency Control", IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 54, pp.251-270, 2007.
3. J. L. Lopez, J. Verd, A. Uranga, J. Giner, G. Murillo, F. Torres, G. Abadal, and N. Barniol, "A CMOS–MEMS RF-Tunable Bandpass Filter Based on Two High-Q 22-MHz Polysilicon Clamped-Clamped Beam Resonators", IEEE Electron Device Lett., vol. 30, pp. 718-720, 2009.
4. R. Cheung, "Silicon carbide micro electromechanical systems", Imperial College Press, 2006.
5. V. Cimalla, J. Pezoldt, and O. Ambacher, "Group III nitride and SiC based MEMS and NEMS: materials properties, technology and applications", J. Phys. D: Appl. Phys., vol. 40, pp. 6386–6434, 2007.
6. D. L. DeVoe, "Piezoelectric thin film micromechanical beam resonators", Sens. and Act. A, vol. 88, pp. 263-272, 2001.
7. E. Mastropaolo, I. Gual, G. Wood, A. Bunting, and R. Cheung, "Piezoelectrically driven silicon carbide resonators", J. of Vacuum Science and Technology B, vol. 28, pp. C6N18-C6N23, 2010.
8. B. Sviličić, E. Mastropaolo, B. Flynn, and R. Cheung, "Electrothermally Actuated and Piezoelectrically Sensed Silicon Carbide Tunable MEMS Resonator", IEEE Electron Device Lett., vol. 33, no. 2, pp. 278-280, 2012.
9. E. Mastropaolo, B. Sviličić, T. Chen, B. Flynn, R. Cheung, "Piezo-electrically Actuated and Sensed Silicon Carbide Ring Resonators", Microelectronic Engineering, vol. 97, pp. 220-222, 2012.
10. B. Sviličić, E. Mastropaolo, T. Chen, and R. Cheung, "Piezoelectrically Transduced Silicon Carbide MEMS Double-Clamped Beam Resonators", J. of Vacuum Science and Technology B, vol. 30, no. 6, atr. no. 06FD05, 2012.
11. R. A. Johnson, "Mechanical Filters in Electronics", Wiley, 1983.
12. G.J. T. Leighton, P.B. Kirby, H. J. Colin, and C.H.J. Fox, "In-plane excitation of thin silicon cantilevers using piezoelectric thin films", Appl. Phys. Lett., vol. 91, pp. 183510-183512, 2007.
13. NovaSiC, see http://www.novasic.com.
14. Inostek, Inc., see http://www.inostek.com.
15. K. Zheng, J. Lu, and J. Chu, "A Novel Wet Etching Process of Pb(Zr,Ti)O3 Thin Films for Applications in Microelectromechanical System", Jpn. J. Appl. Phys., vol. 43, pp. 3934-3937, 2004.
16. L. Jiang, R. Cheung, R. Brown, and A. Mount, "Inductively coupled plasma etching of SiC in SF_6/O_2 and etch-induced surface chemical bonding modifications", J. of Appl. Physics, vol. 93, pp. 1376-1383, 2003.
17. F. R. Blom, S. Bouwstra, M. Elwenspoek, and J. H. J. Fluitman, "Dependence of the quality factor of micro-machined silicon beam resonators on pressure and geometry", J. of Vacuum Science and Technology B, vol. 10, pp. 19-26, 1992.
18. H. Chandrahalim, S.A. Bhave, R. Polcawich, J. Pulskamp, D. Judy, R. Kaul, and M. Dubey, "Performance comparison of $Pb(Zr_{0.52}Ti_{0.48})O_3$-only and $Pb(Zr_{0.52}Ti_{0.48})O_3$-on-silicon resonators", Appl. Phys. Lett., vol. 93, pp. 233504-233504-3, 2008.
19. Q. M. Wang, T. Zhang, Q. Chen, and X.H. Du, "Effect of DC bias field on the complex materials coefficients of piezoelectric resonators", Sens. and Act. A, vol. 109, pp. 149-155, 2003.
20. P. B. Karabalin, M.H. Matheny, X.L. Feng, E. Defaÿ,G. Le Rhun, C. Marcoux, S. Hentz, P. Andreucci, and M. L. Roukes, Appl., "Piezoelectric Nanoelectromechanical Resonators Based on Aluminum Nitride Thin Films", Phys. Lett. 95, pp. 103111-103111-3, 2009.

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