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Temperature stability of electro-thermally and piezoelectrically actuated silicon carbide MEMS resonators

G.S. Wood*, I. Gual, P. Parmiter, R. Cheung

School of Engineering, University of Edinburgh, Scottish Microelectronics Centre, The King's Buildings, West Mains Road, Edinburgh, EH9 3JF, United Kingdom

*Corresponding author. Tel.: +44 131 650 5610; fax: +44 131 650 7475.
E-mail address: g.s.wood@ed.ac.uk (G.S. Wood)

Abstract

The influence of temperature between 10˚C and 100˚C on the frequency shift of electro-thermally actuated silicon carbide (SiC) clamped-clamped beams and piezoelectrically actuated SiC cantilevers has been studied. For electro-thermally actuated beams, it has been found that the rate of change of frequency varies from around ±530ppm/˚C to around ±20ppm/˚C. The differential stress of the different materials has been found to play an important role in the temperature stability of the resonators. The shifts in frequency have been shown to decrease as the temperature increases above 40˚C, attributable to the converging coefficients of thermal expansion (TCEs) of Si and SiC, resulting in reduced stress at the anchors, confirmed by simulations. Platinum, rather than aluminium, has been found to be a superior material for use as actuation electrodes because the TCEs of platinum and SiC are better matched, and converge as the temperature increases, leading to less induced stress. A larger electrode area on top of the structure can result in the thermal stress being more evenly distributed, which can improve the temperature stability, as measured with devices with a larger area of Pt electrodes as well as piezoelectrically actuated cantilevers with the electrodes covering the entire length, rather than half the length, of the cantilevers.

Keywords: Silicon carbide, electro-thermal actuation, temperature reliability, resonators

1. Introduction

Micromechanical resonators fabricated from silicon carbide (SiC) are expected to function more reliably compared to their silicon (Si) counterparts [1]. The advantages of using SiC lie with the physical properties of the material including its chemical inertness, resistance to radiation and mechanical durability [2], as well as the fact that SiC structures can resonate at higher frequencies than Si structures of identical dimensions, due to SiC's relatively lower mass density and higher Young's modulus [3].

In order to utilise SiC microelectromechanical systems (MEMS), the reliability of the devices over a range of different temperatures needs to be understood and characterised. Previous studies on SiC resonators have investigated the stability of the resonant frequency over a temperature range between 20˚C and 60˚C [4] and between 20˚C and 700˚C [5] and found frequency shifts of -22ppm/˚C and -25ppm/˚C respectively. In both cases, the device tested had been a laterally oscillating resonator actuated using an electrostatic method. Another study with an electrostatically actuated free-free beam anchored at the centre has reported a frequency shift of -32ppm/˚C between 20˚C and 90˚C [6].

In this paper, we report on the first investigation of the shift in frequency of electro-thermally actuated SiC clamped-clamped beams and piezoelectrically actuated SiC cantilevers between temperatures of 10˚C and 100˚C. Two additional factors that affect device performance have been studied, namely, 1) the actuation electrode material and 2) the actuation electrode's position on top of the devices.

2. Experimental

In this study, three different device structures have been fabricated for temperature characterisation. For each device, a 2.3µm thick layer of single-crystalline 3C-SiC has been grown on a Si substrate, using a two-step, carbonisation-based, atmospheric pressure chemical vapour deposition process [7]. A 100nm layer of thermal oxide has been grown before a further 200nm has been deposited using plasma-enhanced chemical vapour deposition (PECVD).

2.1 Electro-thermal actuators

Aluminium (Al) and platinum (Pt) have been used as the electrodes for electro-thermal actuation on SiC clamped-clamped beams. For each design, the metal (Al or Pt) has been deposited, patterned and etched to create electrodes that have an input resistance of around 50**Ω**, resulting in Al electrodes with a width of 4µm and Pt electrodes with a width of 15µm. The actuation electrodes have been patterned on only half of the beam length because this configuration results in optimal actuation efficiency [8]. The SiC clamped-clamped beams have been fabricated using a process detailed elsewhere [9]. The beams have been designed to be 200µm in length giving a nominal resonant frequency (f_0) of 659kHz, calculated using the equation [3]

$$f_0 = 1.03\sqrt{\frac{E}{\rho}}\frac{t}{L^2} \qquad (1)$$

where E is the Young's modulus and ρ and t are the density and thickness of the SiC respectively. The value of Young's modulus used for the resonance calculation is 400GPa and for the density is 3230kg/m^3 [5]. In the present experiments, a laser vibrometer has been used to detect the output resonant frequency of the devices, although as output electrodes, polycrystalline-silicon tracks (for piezoresistive sensing) and a Pt/PZT/Pt stack (for piezoelectric sensing) have been deposited for the possible electrical sensing of the beam vibration. Fig. 1 and Fig. 2 show the structure of the Al and Pt electro-thermal actuation devices respectively.

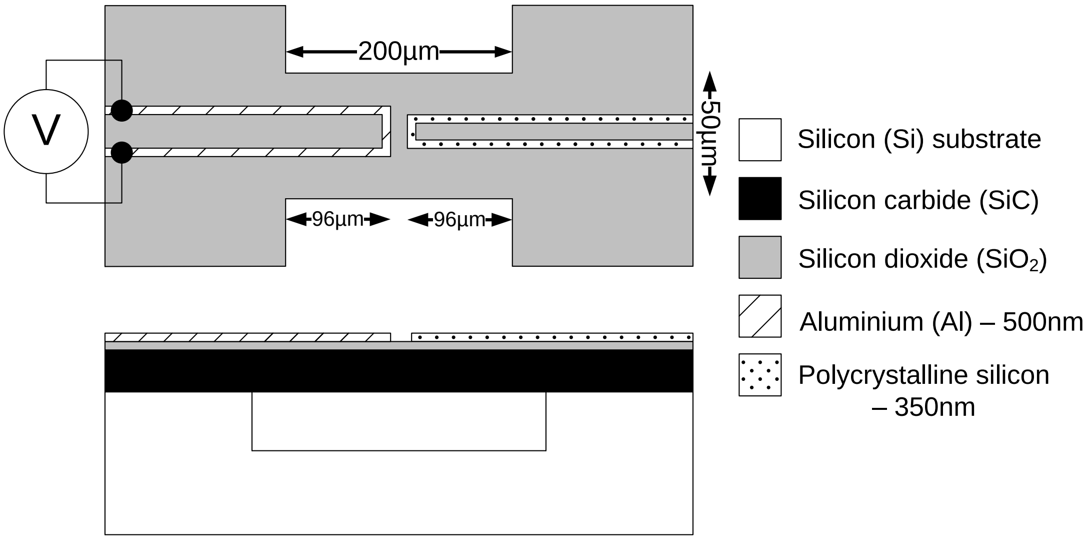


Fig. 1. Plan and side view of electro-thermal clamped-clamped beam actuator design (Al actuation). Poly-Si electrodes shown are not used.

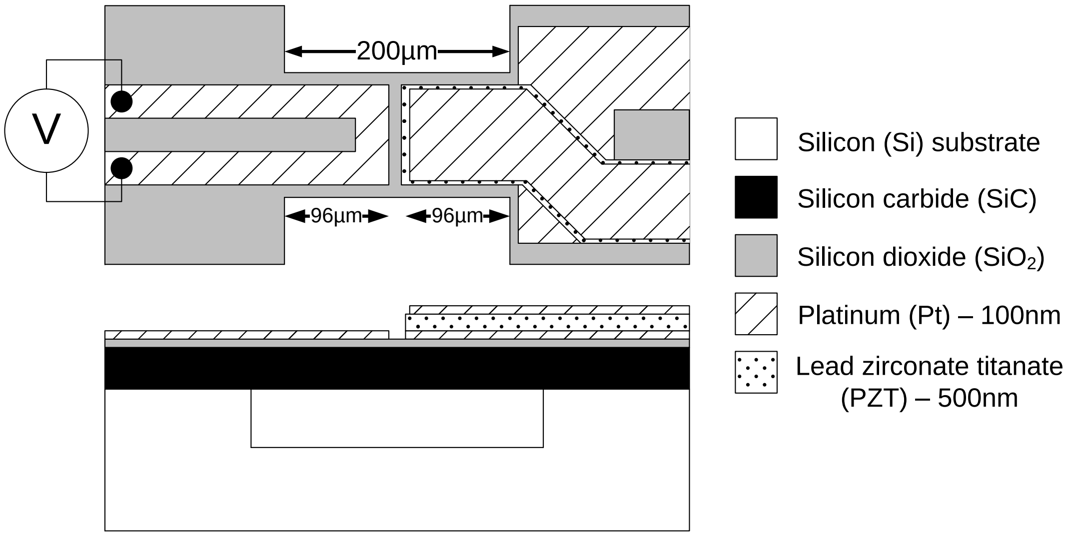


Fig. 2. Plan and side view of electro-thermal clamped-clamped beam actuator design (Pt actuation). Pt/PZT/Pt stack shown is not used.

2.2 Piezoelectric actuators

For the third device design, a stack of lead zirconate titanate (PZT) sandwiched between two layers of Pt has been used as electrodes for piezoelectric actuation on a SiC cantilever. The Pt/PZT/Pt layers have been deposited and then, in turn, patterned using photolithography and etched using argon milling for the Pt and a chemical etchant for the PZT in order to expose top and bottom Pt electrodes to bond to. The SiC cantilever has been fabricated using the same process as for the clamped-clamped beam [9]. The cantilevers have been designed to be 200μm in length resulting in a nominal resonant frequency of 90kHz, calculated using the equation [10]

$$f_0 = 0.162\sqrt{\frac{E}{\rho}}\frac{t}{L^2} \qquad (2)$$

The device design is shown in Fig. 3(a) together with a scanning electron micrograph (SEM) image in Fig. 3(b).

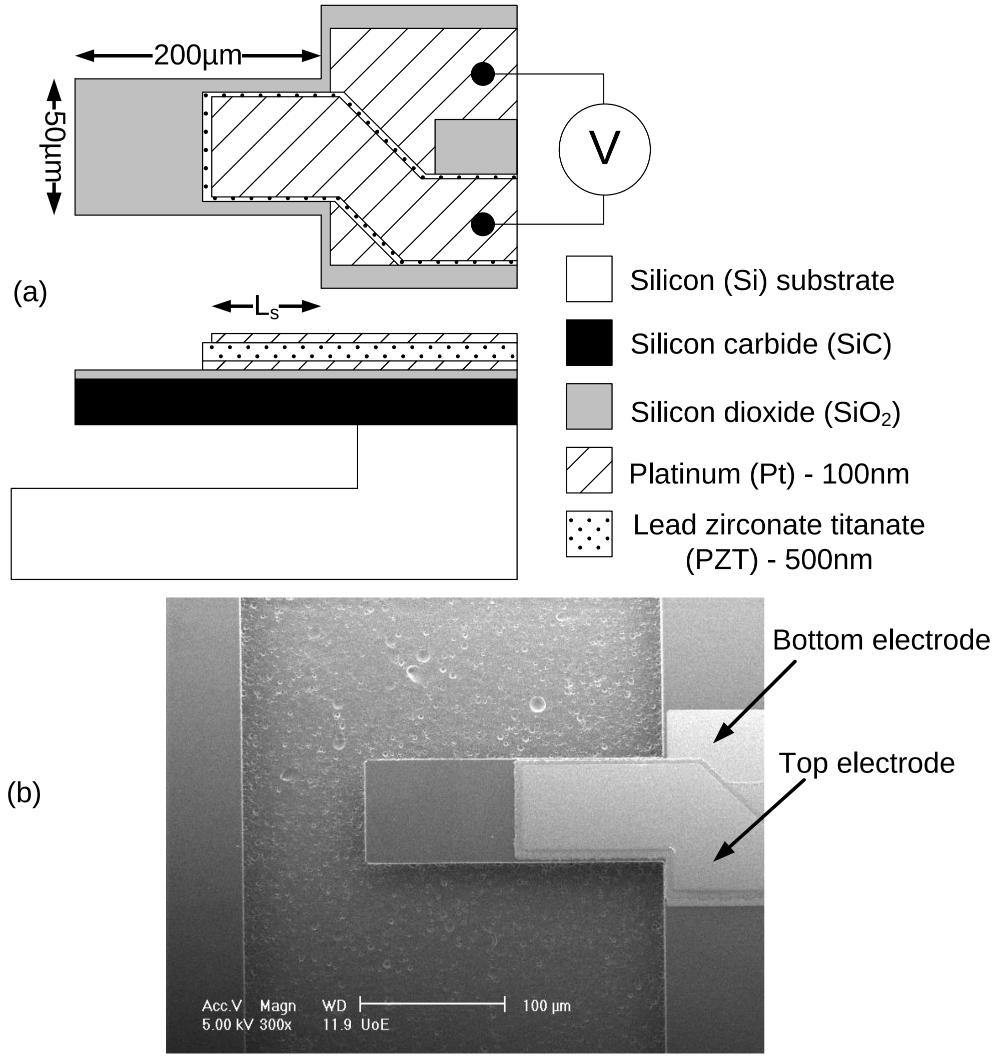


Fig. 3. (a) Plan and side view of piezoelectric cantilever actuator design; (b) SEM image of device

2.3 Measurement set-up

In order to characterise the performance of the devices, each wafer has been placed in a temperature-controlled vacuum chamber at a pressure of 0.001mbar. The temperature has been increased in 15˚C intervals from 10˚C to 100˚C. After each increase, the temperature has been allowed to stabilise. Subsequently, all the devices on each wafer have been actuated in turn by means of an automatic probe station that has been connected to a signal generator performing a frequency sweep with a resolution of 5Hz. Several devices of each design have been actuated, in order for trends to be identified. After each device has been actuated, its resonant frequency and amplitude have been detected by a Polytec MSV-400 laser vibrometer, capable of picometre vibration amplitude resolution. The actuation frequency that produces the largest vibration amplitude is the beam's resonance. The maximum error of the resonant frequency measurements is about 55ppm, which, as will be seen, does not affect the ability to identify trends.

3. Actuation theory

3.1 Electro-thermal actuation

The advantages of electro-thermal actuation compared to other methods such as electrostatic actuation are outlined in [11]. The theory behind electro-thermal actuation has been explained elsewhere [11, 12]. Power is dissipated in the metal (Al or Pt) electrode on top of the SiC beam when the voltage V is applied, resulting in electrical heating. A change in temperature occurs throughout the structure and the difference in thermal expansion coefficients between the beam and the electrode results in a mechanical force being applied. As explained in [11], an AC and a DC component of the applied voltage V are required to ensure that the beam is driven into resonance (f_0) when $V_{ac} = f_0$. In our experiment, the device has been driven into resonance by applying an 8V peak-to-peak ac signal at f_0 together with a 1V dc bias to the input electrodes (see Fig. 1 and 2).

3.2 Piezoelectric Actuation

The advantages of using piezoelectric actuation include simplified fabrication and low power consumption. Due to the crystal structure of PZT, when an electric field is applied to a thin film, a strain is induced [13]. The cantilever structures have been actuated by applying the input signal V_{ac} across the two Pt electrodes, above and below the layer of PZT (see Fig. 3), resulting in a time-varying strain being induced in the PZT at the same frequency as V_{ac}. The expansion of the PZT serves to actuate the

SiC cantilever. In our experiment, the device has been driven into resonance by applying a 0.1V peak-to-peak signal at f_0 with no dc bias to the Pt/PZT/Pt stack.

4. Results and discussion

4.1 Temperature stability of electro-thermally actuated clamped-clamped beams (Al and Pt electrodes)

4.1.1 Effect of thermal stress created at Si/SiC interface at beam anchor

Fig. 4 shows the measured resonant frequency shift in ppm for each 15˚C temperature rise for the devices with Al actuation electrodes. It can be seen that the frequency stability is improved towards 100˚C. Between 10˚C and 40˚C, frequency shifts of ±8000ppm are observed, improving to ±3000ppm between 85˚C and 100˚C.

Our electro-thermally actuated devices display temperature stability of up to ±530ppm/˚C, higher than previous reports of between -22ppm/˚C and -32ppm/˚C [4, 5, 6], achieved using different structure designs and electrostatic actuation.

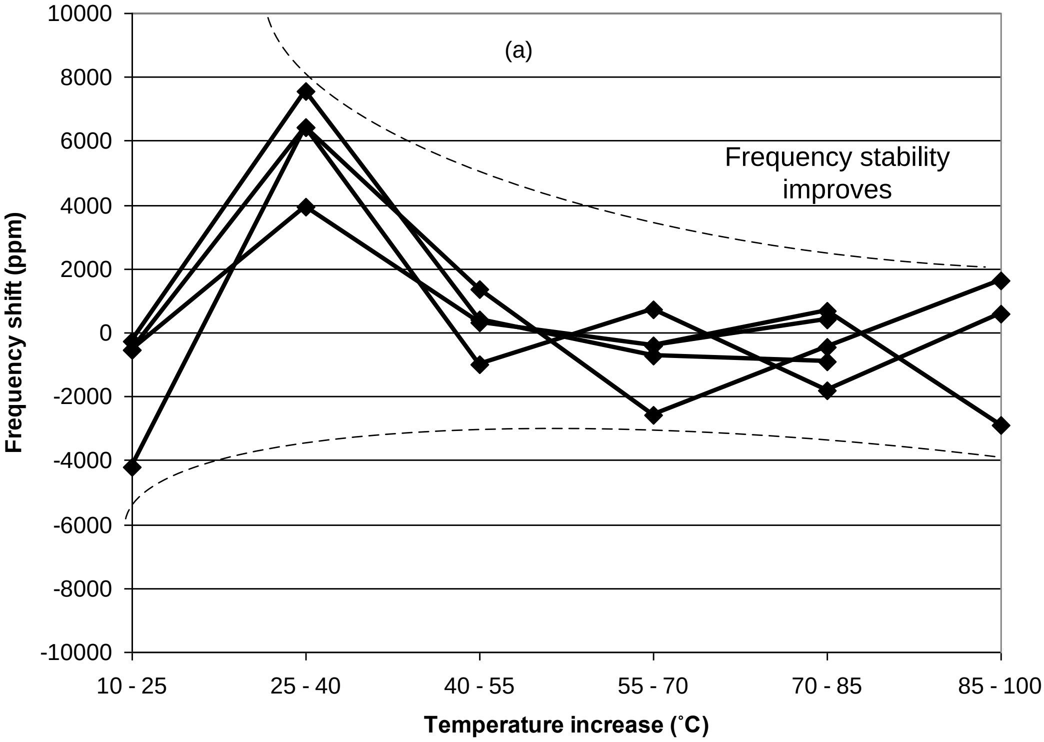


Fig. 4. Electro-thermal actuation with Al electrodes: frequency shift with temperature. Multiple data lines represent measurements from multiple devices of the same design.

As the temperature is increased, the different materials of the structure expand. The rate at which a material expands is governed by its thermal coefficient of expansion (TCE). The length, δ_T, that a material will expand in any given direction for a change in temperature, ΔT, is given by the equation

$$\delta_T = \alpha L \Delta T \tag{3}$$

where L is the initial length of the material in the given direction and α is the TCE. If the expansion of the material is impeded by an interface with another material, a thermal stress is induced. This stress, σ, can be represented by

$$\sigma = \frac{\delta . E}{L} \tag{4}$$

where E is the Young's modulus. Combining equations (3) and (4) results in equation (5) that details the stress experienced if the material is prevented from expanding [14].

$$\sigma = \alpha E \Delta T \tag{5}$$

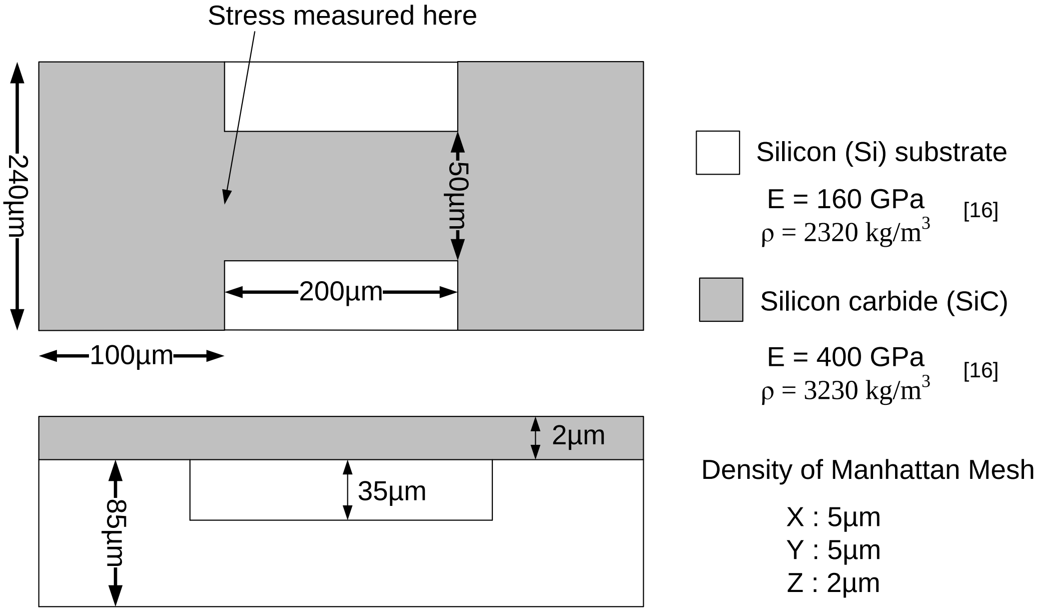
When this stress occurs at the interface of the Si substrate and the SiC beam at the anchor, the anchors expand and the beam is subjected to compressive stress, resulting in a shift of the resonant frequency of the structure [5]. The resonant frequency shift of the beam as a function of stress is given in [15] by the equation

$$\frac{f}{f_i} = \sqrt{1 + \left(\frac{f_0}{f_i}\right)^2 \frac{\sigma_T L^2}{3.4 E t^2}} \tag{6}$$

where f_i is the resonant frequency at the initial temperature and f_0 is the resonance when the beam is not subject to any stress, σ_T is the stress caused by the thermal expansion of the anchors and t is the thickness of the beam.

The improving frequency stability exhibited in Fig. 4 as the temperature is increased is probably due to the relative change in the TCEs for SiC and Si, as a function of temperature. The relative change in the TCE for the SiC and Si would induce a relative difference in the stress at the anchors where the SiC beam meets the Si substrate. As the temperature increases toward 100˚C, the difference between the two materials' TCEs narrows [5]. Subsequently, the stress at the anchors increases less rapidly, lessening the impact on the beam's resonance shift.

In order to confirm the relationship between temperature and anchor stress, a SiC clamped-clamped beam with Si anchors has been simulated using CoventorWare. The model that has been created is illustrated in Fig. 5 together with the material properties obtained from literature [5, 16] and mesh settings. The temperature of the entire model has been increased from 10˚C to 100˚C at 15˚C intervals. For each temperature, the stress has been measured at the location shown in Fig. 5.



Temperature / ˚C	TCE of SiC (10^{-6}/˚C) [5]	TCE of Si (10^{-6}/˚C) [16]
0	2	2.475
10	2.1	2.545
25	2.25	2.65
40	2.4	2.755
55	2.55	2.86
70	2.7	2.965
85	2.85	3.07
100	3	3.175

Fig. 5. Design and set-up of CoventorWare simulation model.

Fig. 6 shows the change in stress at the anchor for each 15˚C temperature rise. As can be seen, the change in stress decreases by 60% as the temperature increases from 10˚C to 100˚C.

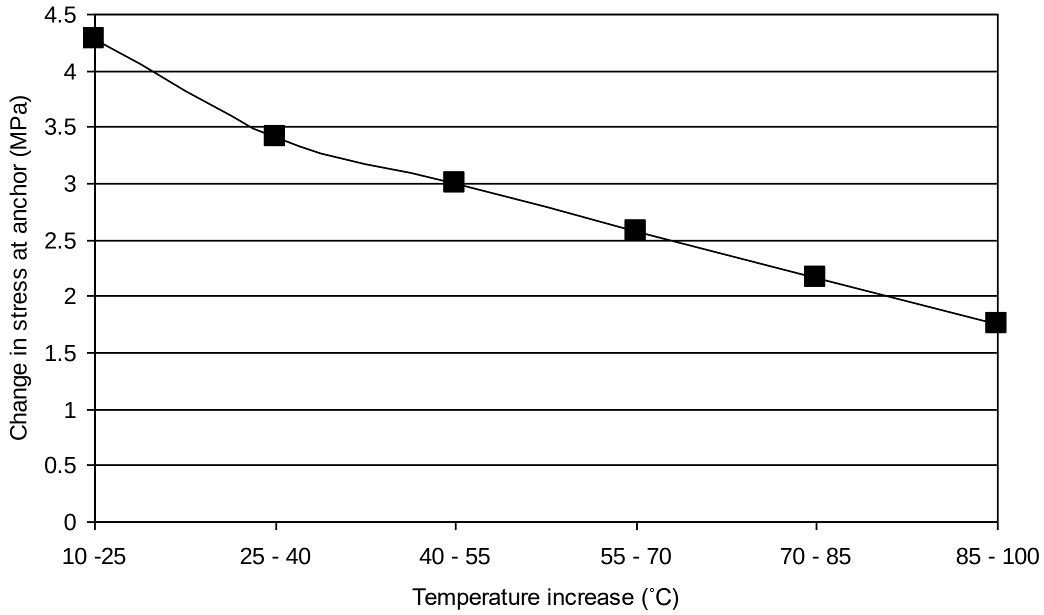


Fig. 6. Simulated change in stress of SiC at Si/SiC interface at anchor for each 15˚C temperature rise

4.1.2 Effect of thermal stress created at SiC/Al and SiC/Pt interfaces

In order to allow for a comparison between the frequency behaviour of the Al and Pt actuated devices, Fig. 7 shows the measured resonant frequency shift in ppm for each 15˚C temperature rise for the devices with Pt actuation electrodes. It can be seen that, between 25˚C and 85˚C, the frequency does not shift by more than ±1500ppm for each 15˚C temperature rise. Across the entire range of 10˚C to 100˚C, the frequency shift does not exceed around ±4000ppm, suggesting a more reliable device compared to the Al actuated devices with resonance shifts of up to ±8000ppm (Fig. 4).

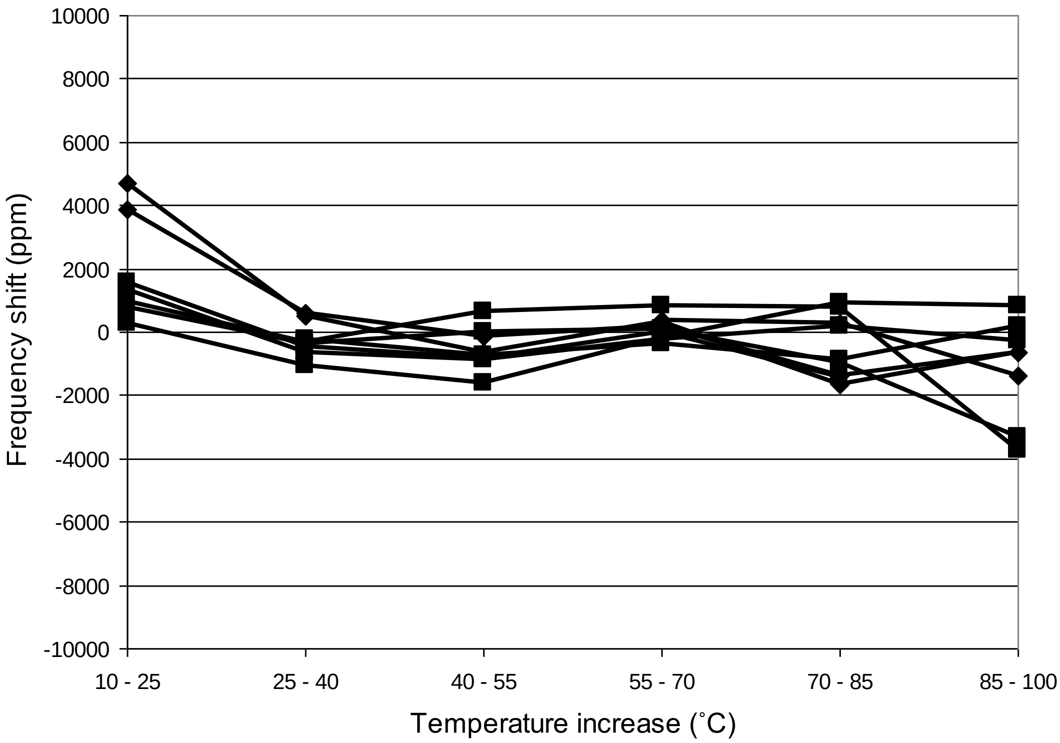


Fig. 7. Electro-thermal actuation with Pt electrodes: frequency shift with temperature. Multiple data lines represent measurements from multiple devices of the same design.

Similar to the relative TCEs of Si and SiC explaining the improved performance of the Al actuated devices as the temperature increases above 40˚C, the difference in temperature behaviour between Al and Pt actuation could be explained by their relative TCEs. As illustrated in Fig. 8, the difference between the TCE of Al and SiC is around 3x larger than the difference in TCE between Pt and SiC. In addition, the TCEs of Al and SiC diverge as the temperature increases, while the TCEs of Pt and SiC converge [16]. As has been explained, with better matched TCEs between layers, there will be less induced stress when the temperature varies leading to a reduced impact on the resonance shift from the beam.

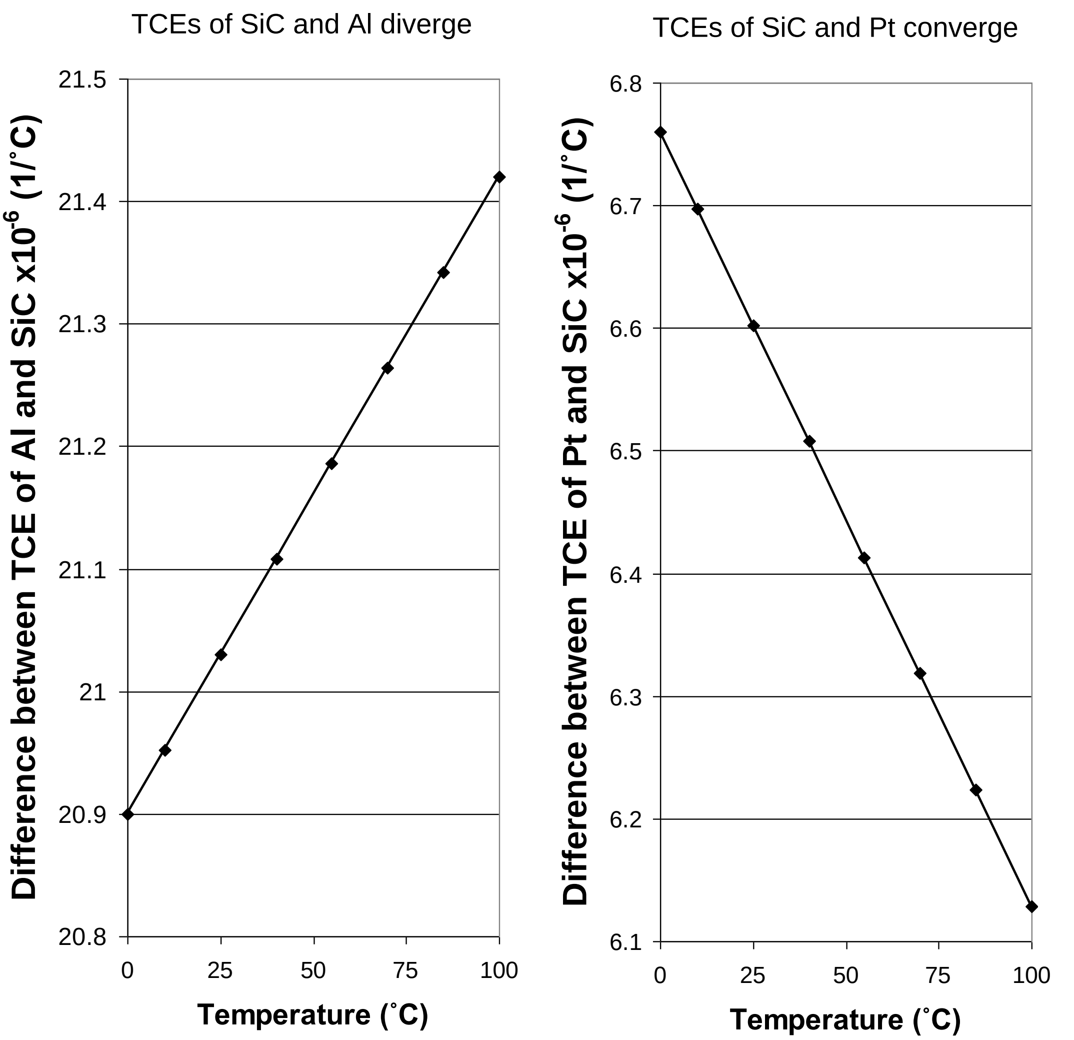


Fig. 8. Change in TCE difference relative to SiC for Al and Pt over temperature range 10˚C - 100˚C. Values obtained from literature [16].

The different electrode areas of the Pt and Al actuated devices (see Fig.1 and Fig. 2) could also play a role in the frequency behaviour of the device. As will be demonstrated in section 4.2 of this paper, better frequency stability can be achieved if a larger area of actuation electrode covers the beam.

4.2 Temperature stability of piezoelectrically actuated cantilevers with different electrode positions

Fig. 9 shows the resonant frequency shift in ppm for each 15˚C temperature rise for the cantilevers actuated using a Pt/PZT/Pt stack. It can be seen that the devices with the Pt/PZT/Pt stack covering the entire length of the cantilever (L_s = 200µm) exhibit better frequency stability, especially between 55˚C and 70˚C, than those with the stack only covering half (L_s = 100µm).

This observation could be explained by the fact that the stress caused by the difference in TCE between SiC, Pt and PZT is induced at the interface of the stack and the cantilever. When this interface only exists halfway along the cantilever, the stress is not induced evenly along the whole length, unlike for the cantilever with the stack covering the entire length. Therefore, as the temperature increases, compared to the fully covered cantilevers, the stress imposed on the half covered cantilevers will probably cause a more dramatic change in the resonance, as can be seen in Fig. 9.

Our piezoelectrically actuated cantilevers exhibit frequency stabilities of up to ±20ppm/˚C for the full length electrode model, a value of which compares favourably to devices that are actuated electrostatically [4, 5, 6].

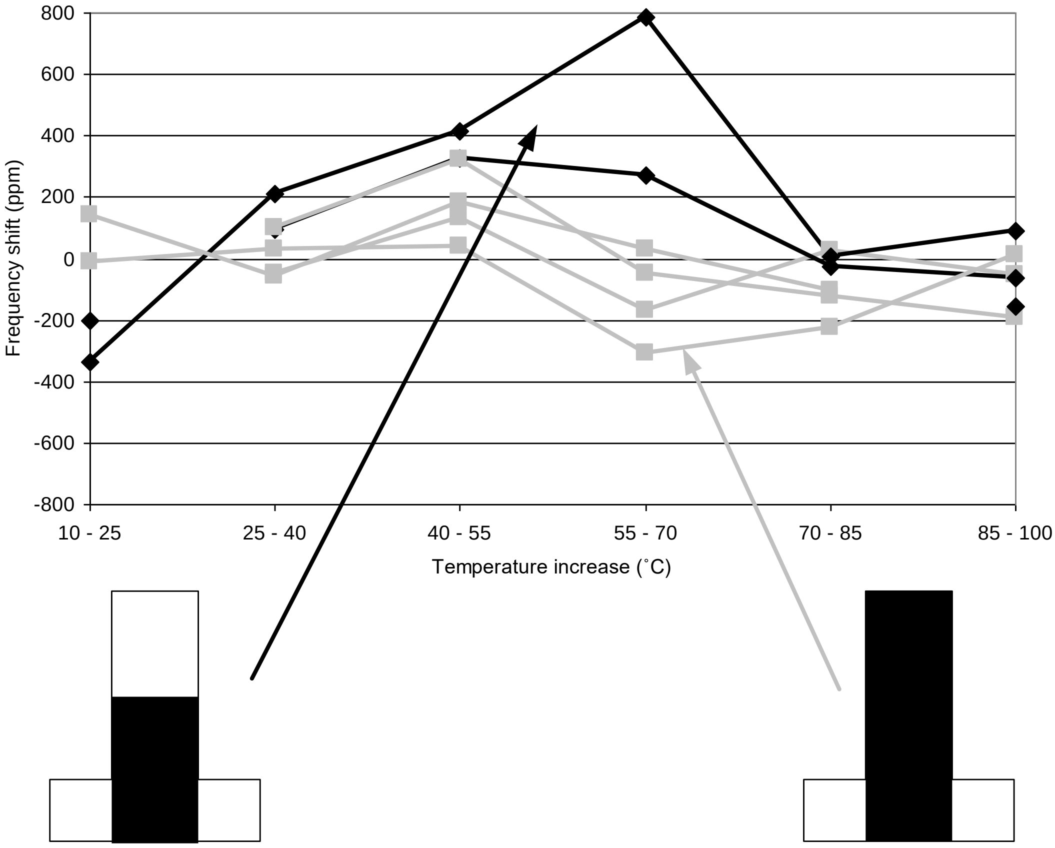


Fig. 9. Frequency shift with temperature: piezoelectric actuation for cantilevers with Pt/PZT/Pt stack covering half the length (black graphs) and the total length (grey graphs). Multiple data lines represent measurements from multiple devices of the same design.

5. Conclusions

For the first time, the stability of the resonant frequency with temperature between 10˚C and 100˚C of electro-thermally actuated SiC clamped-clamped beams and piezoelectrically actuated SiC cantilevers has been presented.

From all the electro-thermally actuated beams that have been tested, it has been found that the rate of change of frequency varies from around ±530ppm/˚C to around ±20ppm/˚C, for any 15˚C temperature rise. The shift in frequency has been found to decrease as the temperature increases above 40˚C. The reason for this improved performance at higher temperatures can be attributed to the converging TCEs of Si and SiC leading to reduced stress at the anchors. These electro-thermally actuated devices display a higher frequency variation as a function of temperature than previous studies that used different structure designs and electrostatic actuation.

Pt has been found to be a better material than Al for use as the electro-thermal actuation electrode on the beams because less frequency shift with temperature has been observed. The superior performance of the Pt actuated devices can be attributed to the TCEs of Pt and SiC being better matched at 10˚C, and then converging as the temperature increases up to 100˚C. In addition, the larger area of the Pt electrodes could also contribute to the improved frequency stability.

The temperature behaviour of the cantilevers has been found to be influenced by the length of the Pt/PZT/Pt electrodes used for actuation. A stack that covers the entire length gives the optimal result of lower frequency variation, probably due to the thermal stress on the cantilever being evenly distributed as the temperature changes. The piezoelectrically actuated cantilevers exhibit frequency stabilities for the full length electrode model that compare favourably with previously reported electrostatic devices.

The above findings can be utilised in the design of SiC MEMS for use in high reliability applications. Today, MEMS resonators are emerging as competitors to quartz crystals in timing applications. SiC MEMS has the potential to perform the same function but with greater temperature stability. SiC MEMS could also be used for various high-frequency communication applications where its higher resonating frequencies combined with its better temperature stability will be an advantage.

Acknowledgments

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