Journal of Mechatronics
Vol. 1, 21–24, 2012

Electrostatically Actuated 3C-SiC MEMS for Frequency Mixing

Musaab Hassan

School of Mechanical Engineering, Faculty of Engineering, Sudan University of Science and Technology, Khartoum, 11111, Sudan

RESEARCH ARTICLE

Radio frequency microelectromechanical system (RF MEMS) is a promising technology in the field of wireless communications. MEMS mixers and filters offer remarkable advantages in term of size, cost, and power consumption over conventional devices. One of the MEMS materials that have very good mechanical and electronic characteristics is Silicon carbide (SiC). In this work, A SiC electrostatic actuator, resonating at fundamental frequency of 66.64 kHz, was fabricated and designed to perform frequency mixing. Two signals with different frequencies were multiplied and the sum, as well as the difference of the two frequencies, was used to drive the fabricated cantilever into resonance.

Keywords: MEMS, SiC, Electrostatic Actuation, Micro-Resonator, RF-MEMS

1. INTRODUCTION

A frequency mixer receives two frequencies, a radiofrequency (RF) and a local oscillator (LO) frequency, and outputs their difference frequency or sum frequency. In traditional approaches, the signals have to be filtered after mixing is performed. Filtering is required to reject the images produced after mixing, as shown in Figure 1. However, with the MEMS-based frequency mixers, no filtering is required as the resultant frequency after mixing with the local oscillator is down-converted, or up-converted, as well as filtered at the intermediate frequency.[1,7] A MEMS-based mixer-filter replacing the conventional system is highlighted in Figure 1. When two signals are applied to the electrodes of an electrostatically actuated resonator they get multiplied. The difference or the sum of the two frequencies can drive the MEMS structure into resonance. One problem associated with electrostatically actuated cantilevers is the proportionality between the air gap and the applied voltage while keeping the electrostatic force is unchanged. Decreasing the air gap could lead to sticking problem[8] or the cantilever could snap onto the surface of the substrate. Meanwhile, to achieve high resonance frequencies a further down scaling of MEMS structure, including the surface area of the cantilever (capacitor area), is required. The high $\sqrt{(E/\rho)}$ ratio (Young's Modulus to density ratio) of SiC makes it a good candidate for devices with high resonance frequencies (in the range of UHF, ultra high frequency, which commonly found in communication systems) without having to exceed the critical gap (after which the resonating structure will snap onto the substrate). Silicon carbide also has the capability of being used in harsh environment without loosing much of its mechanical characteristics.[2] 3C-SiC bridge actuated at frequency of 632 MHz was fabricated and tested.[6] Cheung et al.[4] presented an electrothermal Al/SiC cantilever for the purpose of mixing two signals and the maximum vibration amplitude was only 62 nm when the applied voltage was 4 volts. Hassan[8] also showed a 3C-SiC electrothermal mixer but with higher vibration amplitude (few hundred nanometres) when the applied voltage was only 0.5 volt. In this work, signal mixing was performed using an electrostatically actuated SiC cantilever instead of the reported electrothermally actuated SiC mixers. The achieved results with the electrostatic actuator are comparable with comparable with the electrothermal one[8] in terms of the required voltage and the level of actuation.

2. FABRICATION OF CANTILEVERS WITH ELECTROSTATIC ACTUATION

To achieve electrostatic actuation, the device structure needs to include an insulating layer. This was achieved by employing 3C-SiC deposited on a poly Si/SiO_2/Si wafer. The thicknesses were 3 μm, 1.5 μm, and 500 μm respectively. A schematic diagram of the fabricated layers is shown in Figure 2. Nichrome, which had proved to form a good ohmic contact with SiC (Davis and Robert 1995), was deposited at room temperature. The nichrome was also used as a mask for the inductively coupled plasma dry etching process. The SiC layer was anistropically etched

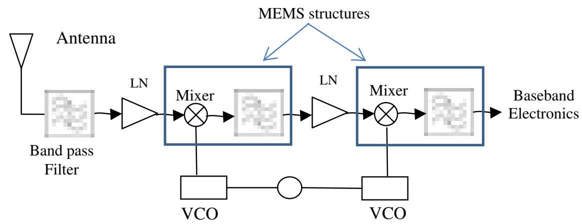

Fig. 1. Simple block diagram for wireless receiver, replacing the shaded area with a micromechanical device (Nguyen and Wong 2004).

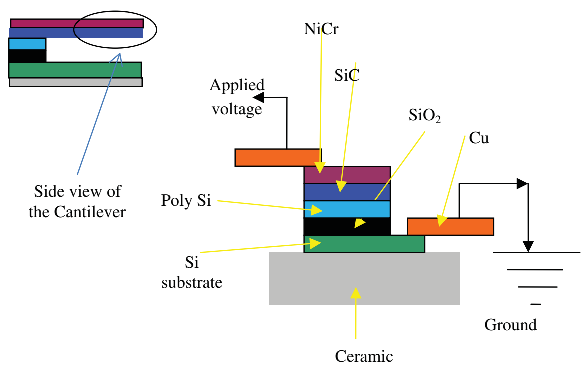

Fig. 2. Structure layout.

and the polycrystalline Si layer was isotropically etched to release the SiC cantilevers. More details about the fabrication process are given where else.[3] A set of cantilevers with different lengths were released but the tests were carried out on the 200 μm cantilever which has a width and thickness of 15 μm and 2 μm respectively.

3. THEORY

Two parallel plates with applied voltage, V, and separated with small gap, g, generate an electrostatic force, F, in a direction normal to the plates' areas which is the first derivative of the energy, U, stored between the plates;

$$F = \frac{\partial U}{\partial x} = \frac{\partial C}{\partial x} V^2 = \frac{\varepsilon A}{2g^2} V^2 \tag{1}$$

C is the capacitance which is equal to $\varepsilon A/g$, A is the overlapping area, x is the displacement of moving plate, and ε is permittivity of the medium between the plates (vacuum). Therefore, the electrostatic actuation is dependent on the square of applied voltage.[3] If different voltages $V_{\mathrm{RF}} \cos \omega_{\mathrm{RF}} t$ and and $V_{\mathrm{LO}} \cos \omega_{\mathrm{LO}} t$ are applied to the plates, the voltage seen by the capacitor is the difference between these two voltages; $V = V_{\mathrm{RF}} \cos \omega_{\mathrm{RF}} t - V_{\mathrm{LO}} \cos \omega_{\mathrm{LO}} t$. ω_{RF} represents the radio frequency while ω_{LO} represents the frequency of the local oscillator. The electrostatic actuation force will now be dependent on the square of the above term which will have components at frequencies $\omega_{\mathrm{RF}} + \omega_{\mathrm{LO}}$, and $\omega_{\mathrm{RF}} - \omega_{\mathrm{LO}}$. The ω_{LO} could be chosen so that resulting intermediate frequency, ω_{IF}, is the fundamental frequency of the cantilever. The sum or the difference frequency, when matches the fundamental frequency of the cantilever can drive it into resonance. The capacitively driven cantilever therefore acts as a mixer and filter.

The amplitude of actuation depends on the magnitude of applied voltages; V_{RF} and V_{LO}. The effect of the electrostatic force on the cantilever can be thought of as distributed load acting on it. This relationship between the applied electrostatic force and the amplitude of actuation can be found by applying bending beam theory. For a beam with length, L, and distributed load intensity w N/m^2, the relation between bending moment, M, and the deflection of the beam, y, along the direction of the beam length, x, is given as;

$$M = \frac{1}{E \cdot I} \frac{\partial^2 y}{\partial x^2} \tag{2}$$

By integrating the above equation and applying the boundary conditions ($\partial^2 y/\partial x^2 = y = 0|_{x=L}$), the maximum deflection of the cantilever (at $x = 0$) can be expressed as;

$$\delta = \frac{w \cdot L^4}{8E \cdot I} \tag{3}$$

E and I are the Young's Modulus and first moment of area respectively where $I = bd^3/12$; b is the width of the cantilever and d is the thickness.

The equivalent mechanical force is;

$$F_M = w \cdot L = \frac{8E \cdot I \cdot \delta}{L^3} \tag{4}$$

For $V_1 = V_{\mathrm{RF}} \cos \omega_{\mathrm{RF}} t$ and $V_2 = V_{\mathrm{LO}} \cos \omega_{\mathrm{LO}} t$ the magnitude of the electrostatic force at $\omega_{\mathrm{RF}} + \omega_{\mathrm{LO}}$, and $\omega_{\mathrm{RF}} - \omega_{\mathrm{LO}}$ is;

$$F_e = \frac{\varepsilon A}{2g^2} V_{\mathrm{RF}} V_{\mathrm{LO}} \tag{5}$$

This mechanical force is equal to electrostatic force; therefore equating Eqs. (4) and (5), would give the relationship between the maximum amplitude of actuation and the applied voltages as;

$$\delta = \frac{\varepsilon \cdot A \cdot L^3}{16 \cdot g^2 E \cdot I} V_{\mathrm{RF}} V_{\mathrm{LO}} \tag{6}$$

4. EXPERIMENTAL SETUP

The beam was excited mechanically using piezo disc to determine the location of resonance frequency. The piezodisc is used to derive beams mechanically into resonance. Wax was used to fix the samples onto the piezoelectric disc. All dynamic measurements were carried out in a vacuum using a chamber that is sealed with a rubber O-ring which allows a minimum pressure. A detailed diagram describing the equipment and the setup can be found where else.[8] The vacuum level provided inside the chamber was

0.016 mbar. Devices were viewed on a monitor shown in the above diagram using a profilometer system. The stage control was used to locate the laser beam on the desired part of the device so that the laser beam could be located precisely. This step was carried out prior to application of electrostatic voltages. It is expected that the resonance frequency can easily be detected (by having a high amplitude of vibration and good quality factor) using external excitation, e.g., piezo-disc. The fundamental resonance was found to be 66.6 kHz.

Next, voltage was applied through cupper plates as shown in Figure 2. The testing was performed on 3 μm SiC beams on poly Si/SiO2/Si as shown in Figure 2. NiCr was deposited on the SiC to serve as a masking layer as well as the top electrode for electrostatic actuation. The cantilever was driven electrostatically at the same resonance frequency detected with the piezo-disc (66.6 kHz).

5. FREQUENCY MIXING: RESULTS AND DISCUSSION

The electrostatically actuated SiC beam presented previously was used to frequency mix two signals. The signals were applied to the driving electrodes as shown in the Figure 3.

For a particular cantilever that resonates at 66.64 kHz, the two applied signals need to have a difference or sum equal to this frequency. Figures 4 and 5 show the resonance detected, using an optical vibrometer, when adding signals or subtracting signals. One signal was fixed at a certain frequency (40 kHz) which is equivalent to the fixed signal in the filtering system (known as local oscillator frequency). The other applied signal, to drive the cantilever into resonance, was 26.64 kHz. This shows that the two signals have been added successfully to resonate at frequency 66.64 kHz which is the resonance frequency of the cantilever. The same has been applied for subtraction (down-conversion) where in this case the other signal is at 106.64 kHz. It should be noted that none of the frequencies used above was able to drive the beam into resonance, which shows that the actuation was carried by the sum or the difference of the two applied signals.

When both applied voltages are 0.5 volt, the maximum measured deflection was about 400 nm. Theoretically Eq. (6) should give the same value for deflection when substituting other values into the equation if no undercutting was present. Undercutting, which was not measured in this work, affects both the characteristic length of the cantilever as well as the overlapping area. But fortunately, the increase of the overlapping area improves the electrostatic force. Substituting a characteristic length of 2 mm, instead of 0.2 mm, would satisfy the equation.

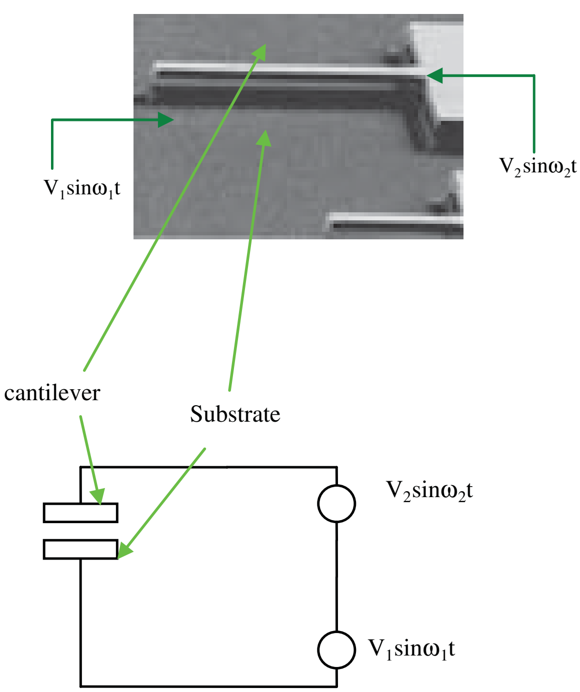

Fig. 3. Circuit diagram of the signal multiplication on electrostatic cantilever.

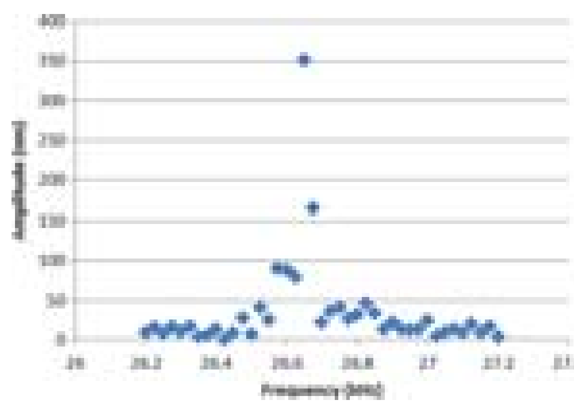

Fig. 4. Resonance detected when varying one signal (between 26.2 kHz and 27.2 kHz) while keeping the other signal fixed at 40 kHz.

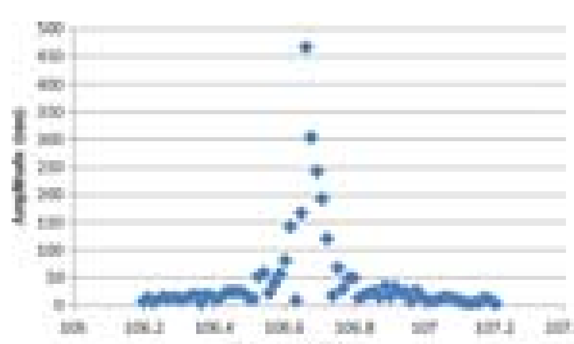

Fig. 5. Resonance detected when varying one signal (between 106.2 kHz and 107.2 kHz) while keeping the other signal fixed at 40 kHz.

Comparing these results with the ones achieved with the electrothermal mixer,[8] the amplitude of actuation is in the same order of magnitude (in the range of few hundreds nanometres) while the applied voltage is also less than one volts. In comparison with Cheung et al.[4] electrothermal Al/SiC device, the amplitude of actuation in this work is higher by almost one order of magnitude while applied voltage here is only one forth.

Although the frequency mixing has been demonstrated by driving the cantilever into resonance using the sum and the difference of two frequencies, but the realisation of a mixer that can be integrated electronically requires adding a suitable sensing mechanism. This sensing mechanism could be another sensing capacitive electrode or a piezoelectric material built in the cantilever. Only then the output of the device would be a voltage or current having frequency at ω_{IF}.

6. CONCLUSIONS

Silicon carbide is a promising material for radio frequency (RF)-MEMS due to its high young's modulus to density ratio. An electrostatically actuated SiC cantilever was fabricated to perform frequency mixing. Two signals were multiplied. The difference and the sum of the signals were used to drive the device into resonance at 66.64 kHz. The electrostatic frequency mixers has an amplitude of actuation of few hundreds nanometres when applied voltage is only 0.5 Volts. Both 3C-SiC frequency mixers, the demonstrated electrostatic mixer and the reported electrothermal mixer, have an amplitude of actuation which is in same order of magnitude (350∼600 nm) when similar voltages are applied (0.5 Volts).

Acknowledgments: This work was supported by Engineering and Physical Sciences Research Council (EPSRC). Grant No. GR/R38019/01 and was carried out in UK. The author would like to thank Dr. Alun Harris, from University of Newcastle upon Tyne, for his suggestion to carry out this work as well as Professor Burdess from same University for his assistance.

References

1. Y. H. Ahn, S. C. Hohng, D. S. Kim, E. K. Kim, S. W. Koch, Y. S. Lim, T. Meier, J. Y. Sohn, J. C. Woo, J. S. Yahng, and K. J. Yee, From excitation resonance to frequency mixing in GaAs multiple quantum wells. *Phys. Rev. Lett.* 82, 3879 (**1999**).
2. J. Burdess, R. Cheung, A. Harris, L. Jiang, M. Hassan, K. Lee, M. Mehregany, G. Phelps, M. Pozzi, N. Wright, and C. Zorman, Mechanical properties of a 3C-SiC film between room temperature and 600 °C. *J. Phys. D: Appl. Phys.* 40, 3335 (**2007**).
3. J. Burdess, R. Cheung, A. Harris, L. Jiang, M. Hassan, M. Mehregany, and C. Zorman, Dry release fabrication and testing of SiC electrostatic cantilever actuators. *Microelectronic Engineering* 78, 106 (**2005**).
4. R. Cheung, I. Gual, and E. Mastropaolo, Silicon carbide electrothermal mixer-filters. *Electron. Lett.* 46, 62 (**2010**).
5. R. F. Davis and L. M. Porter, A critical review of ohmic and rectifying contacts for silicon carbide. *Mater. Sci. Eng.* 34, 83 (**1995**).
6. K. L. Ekinci, X. M. H. Huang, M. Mehregany, M. L. Roukes, Y. T. Yang, and C. A. Zorman, Nanoelectromechanical silicon carbide resonators for ultra high frequency applications. Tech. Digest. Solid-State Sensor, Actuator and Microsystems Workshop, Hilton Head Island, SC (**2000**), pp. 367–8.
7. I. Globespanvirata, C. Nguyen, and A.-C. Wong, Micromechanical mixer+filters "mixlers". *J. Microelectromechanical Systems* 13, 100 (**2004**).
8. H. Musaab, Pt/3C-SiC electrothermal cantilever for MEMS-based mixers. *J. Microsystem Technol.* 17, 425 (**2011**).

Received: 16 April 2012. Accepted: 8 June 2012.