Design of Polycrystalline 3C-SiC Micro Beam Resonators with Corrugation

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On the purpose of increasing resonant frequency without sacrificing quality factor as well as much decreasing dimensions, corrugated micro beam resonator based on polycrystalline 3C-SiC films is the applicable solution. In this work, appropriate corrugated structure is suggested to increase resonant frequency of resonators. Micro beam resonators based on 3C-SiC films which have a two-side corrugation along the length of beams were simulated by finite element method and compared to a same–size flat rectangular. With the dimension of 36x12x0.5 μm^3, the flat cantilever has resonant frequency of 746 kHz. Meanwhile, with this size but corrugation width of 6 μm and depth of 0.4 μm, the corrugated cantilever reaches the resonant frequency at 1.252 MHz.

Keywords : 3C-SiC, Resonator, Corrugation, Resonant frequency

1. INTRODUCTION

According to the rapid growth of communications and sensor techniques, micro mechanical resonators have attractive and intensive interests. In contrast with quartz or surface acoustic wave (SAW) resonators, they have the ability of miniaturizing that makes them possible to become the potential replacement for other resonators on integrated chip design. It's micro-size or even smaller makes it possible to detect infinitesimal object such as gas, cell, DNA etc in chemical and bio sensor applications[1]. Oscillators and filters[2] based on mechanical resonators have higher frequency selectivity characteristics than those of conventional active RC filter[3]. Furthermore, another advance characteristic of this type is low power consumption so that they are appropriate for designing mobile devices.

Today, there are many works of resonators. The result of the high quality factor (>80000) of spring-coupled or parallel resonators driven by multi port electrostatic-comb at vacuum condition has been reported[4]. However as reported in paper[4], this resonator consumed power for active circuit to control quality factor. Among applications of resonators in communications and sensors, there are a great number of applications need mechanical resonators which their structures are in form of micro beam such as cantilever, doubly clammed beam and free-free beam[1,5,6]. Furthermore, these structures have ability of minimizing for on chip resonator, low power consumption and applicability in communications[2,6] as well as sensors applications.

From the Euler-Bernoulli Beam Equation, beam's resonant frequency is

$$f = \frac{\beta^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \tag{1}$$

Where β is the eigenvalues of the equation[7] of beams that depend on their boundary conditions at specific mode e.g. at the first mode: cantilever: β=4.73, doubly clammed beam β=1.875[7], *E* is the Young's modulus, *I* is the inertia moment, ρ is the mass density, *A* is the cross section area of the beam.

The dynamic detection of resonator is preferred to in sensor applications due to its higher sensitivity than that of static detection. Changes in force, mass and temperature will cause a frequency shift of the cantilever. Typically, the mass change Δm which is derived from the resonance frequency shift is calculated from the following formula[8].

$$\Delta m = \frac{k}{4\pi^2}\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \tag{2}$$

Where, k is the spring constant, which can be calculated from Eq. (1), f_1 and f_2 are the resonance frequency of the loaded and unloaded cantilever.

This equation also proves that the mass sensitivity depends on resonant frequency. With the explosion of high speed data transfer devices, the resonant frequency needs to be increased as much as possible. This problem is not only required in communications but also necessary in sensor technique. Si has demonstrated the usefulness of flat type resonators in variety of applications. However, most of them are not suitable for higher requirements of frequency, quality factor, temperature and stability.

The development of micro/nano electro-mechanical system (M/NEMS) technique allows fabricating resonators based on better materials. Recently, it is researched on silicon carbide (SiC) and predicted it as advantageous material in future[9]. In designing mechanical resonators, its first benefit is that its higher Young's modulus, which is approximately 400 - 500 GPa, is the important factor that drives resonant frequency up as seen in Eq. 1. Meanwhile, although there are many woks on resonators based on Si which its mass density of about 2300 kg/m^3 is not much less than that of SiC (approximately 3200 kg/m^3), its Young's modulus is almost about 100 GPa-200 GPa. Moreover, among materials that usually used in MEMS, SiC is one of the highest Young's modulus materials. Resonators based on SiC have advantages not only in high Young's modulus but also many other merits. Some of them are wide-bandgap, high electron mobility, high breakdown field, high thermal conductivity, and relatively large dielectric constant.

SiC promises many applications for resonator where once it was impossible. With the high sublimation temperature at nearly more than 2700 °C and nearly inert in most of chemical, SiC is better in making sensors used in harsh environments. The most common polytypes are hexagonal modifications 6H, 4H and 8H, a rhombohedra polytype 15R, and a cubic polytype 3C. The last one, 3C-SiC occupies a special place, because it is the only polytype possessing a cubic structure (sphalerite type). It can be prepared at much lower temperatures (1473 to 2273 K) than hexagonal polytypes (2473 to 2773 K). There are two kind of 3C-SiC single-crystalline and polycrystalline. Among them, polycrystalline is the most attractive because it overcomes defects of single crystalline such as large residual stress, cracks and large lattice mismatch (20 %). This polycrystalline is expitaxially grown on more types of substrates even on insulating materials as well as non crystalline substrate at lower temperature (1000 - 1200 °C), than single type that is grown restrictively crystalline substrate at higher temperature[10]. Moreover, the grown crystalline quality affects on not only physical and electrical but also mechanical properties of 3C-SiC films. The characteristics of resonators based on M/NEMS depend largely on Young's modulus, the inertia moment and the mass density which different with grown 3C-SiC films[11].

Fabricating resonators based on 3C-SiC is one of the efforts to put up resonant frequency. This paper suggested changing mechanical structure of resonators as another method. In general, frequency is increased by reducing the length of resonator or increasing the thickness. However, in practice this is followed by many problems. Thickness depends on the growing process. 3C-SiC films were expitaxially grown at 1 μm thickness or lower. At higher resonant frequency, flat type resonator whose cross section is rectangular begins to degrade their mechanical and electronic properties when it lengthens and thickens. J. Yang et al reported in[12] many effects of cantilever length on quality factor. Moreover, the limitation of fabrication process does not allow fabricating smaller length.

This work suggested corrugated resonators as a new structure of resonator to overcome those problems. A finite element method is used to analyze this structure. This is the method that effectively analyzes the mechanical properties of corrugated structures. From the flat type resonator of which cross section is rectangular, a change appears on cross section to form corrugated structure as in Fig. 1.

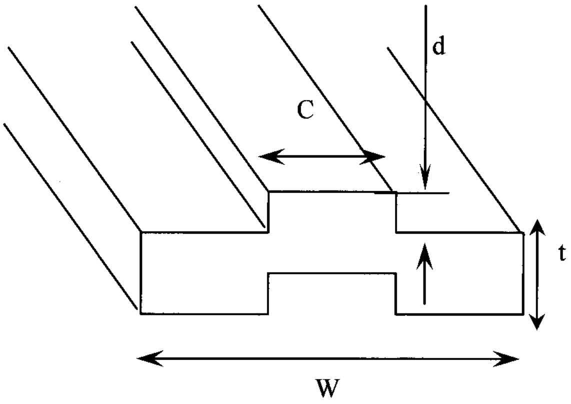

Fig. 1. Geometry of proposed corrugated SiC resonators.

Where, t is the thickness and W is the width of the beam. The corrugation has the width C and the depth d.

The result is expected that changing this structure will increase moment I while the cross section area A does not change. Thus, from equation 1, this is the solution for increasing resonant frequency.

2. MODEL'S GEOMETRY AND MESHING

The ANSYS finite element analysis (FEM) was used to conduct the vibration of corrugated resonators and their vibration modes. Isotropic material properties were used for all models. This based on the properties of polycrystalline 3C-SiC expitaxially grown as presented by G. S. Chung et al in[10]. Then cantilever is made by etching with the method shown by G. S. Chung et al in[13]. For this analysis the Young modulus of 3C-SiC is 448 GPa and Poison ratio of ν=0.23, and mass density ρ=3200 kg/m^3.

This wok has analyzed the affects of corrugation on vibration properties. The first analysis presented the usefulness of corrugation depth. The second found out the optimum width of corrugation.

Figure 2 presents the structure of meshed 3C-SiC corrugated micro beam resonator. This resonator has the width of 12 μm and corrugation is 4 μm wide. APVCD deposition process is carried out to gain the thickness of silicon carbide up to 1 μm. In this simulation, the model thickness is 0.5 or 1 μm. ANSYS software supports many models that help to solve many mechanical structures. With corrugated resonators, because the corrugation depth is much smaller than other dimension of the beam, this model was meshed by smart size to optimum time processing. In this meshing model, the element sizes were chosen smaller near the corrugation edges and lager at the surface of the beam. The SOLID187 was chosen as the element type for meshing. This element is a higher order 3-D and 10-node element. SOLID187 has a quadratic displacement behavior and is well suited to modeling irregular meshes. The structure was modeled by 12000 elements.

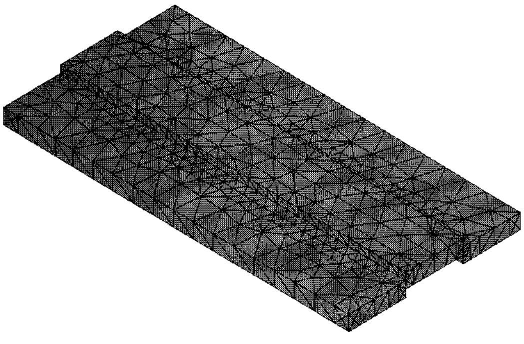

Fig. 2. Smart mesh for corrugated 3C-SiC beams.

For the two types of the structure cantilever and doubly clammed beam, the boundary conditions are different. With the first type, the constraints, the boundary conditions are applied only one end. The surface at this end is fixed. In other end is stimulated by force on nodes or line. In case of model analysis which extracts the vibration modes and their resonant frequency, the stimulus is unnecessary. For doubly clammed beam, its structure is not different from cantilever, but the constraints are applied to both its ends and the stimulus is applied at middle top.

3. RESULTS AND DISCUSSION

The modal analysis gives the vibration properties of corrugated structure. Fig. 3 presents the first four vibration modes of cantilever 36x12x0.5 μm^3 with corrugation of 36x4x0.2 μm^3, which illustrates the vibration states of cantilever at isometric view and right view from mode 1 to 4, respectively. The first mode is showed in Fig. 3(a). In this mode the cantilever vibrated up and down at resonant frequency of 885 kHz. In application, almost only first mode is used because it is simple and has the best quality. In this mode, the vibration is up and down. Although higher modes as shown in Table 1 have higher resonant frequency, they are hardly applied because of the problem of quality factor and stimulus method.

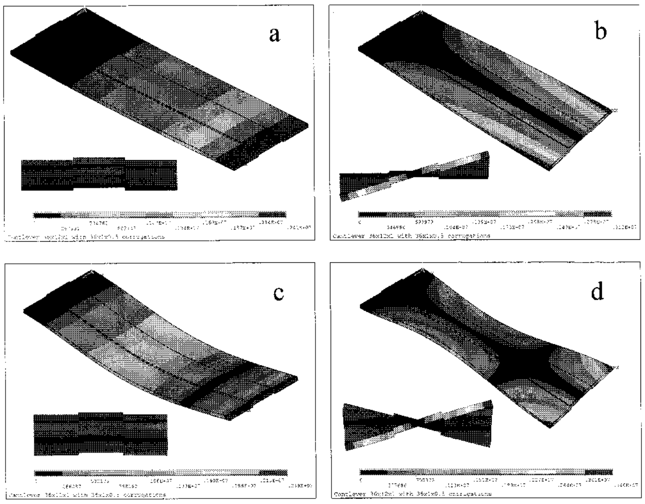

Fig. 3. Vibration modes of cantilever 36x12x0.5 μm^3 with corrugation of 36x4x0.2 μm^3.

Table 1. Resonant frequency of first four modes.

Mode	1	2	3	4
Frequency (MHz)	0.885	4.666	5.426	14.653

This work also analyzed the influence of corrugation depth. 4 corrugated cantilevers and 1 flat cantilever were analyzed. They all have the same length, width and thickness of 36x12x0.5 μm^3 but different corrugation depth. The corrugation width of four corrugated cantilevers is 4 μm but each has corrugation depth of 0.1, 0.2, 0.3 and 0.4 μm respectively. The flat cantilever is modeled with the corrugation depth of 0 μm.

The results proved that resonant frequency is improved by increasing the corrugation depth as shown in Fig. 4. With the corrugation depth of 0.4 μm, the frequency reached 1.2 MHz. This frequency approximately increased 60 % when compared to that of flat type resonators whose frequency is 0.746 MHz.

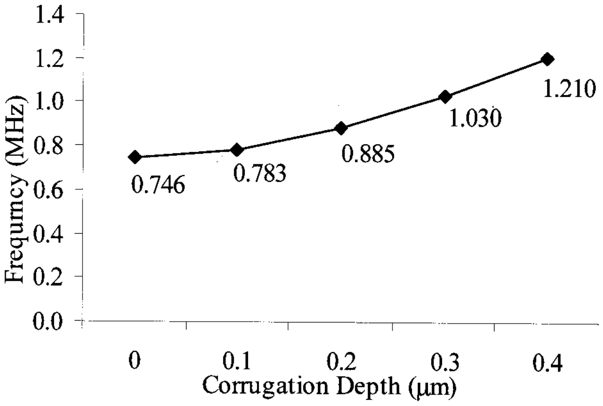

Fig. 4. Resonant frequency of cantilever (36x12x0.5 μm^3) versus corrugation depth.

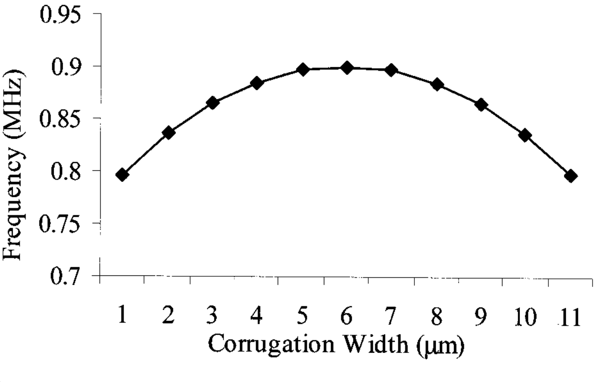

Fig. 5. Effect of corrugation width in 3C-SiC micro resonator.

Corrugation width is also other important parameter that has affect on characteristics of resonator. 12 corrugated cantilevers which all have the same dimensions of 36x12x0.5 μm^3 were analyzed. In this case, the corrugation depth was fixed at 0.2 μm for all cantilevers but their width varied from 1 to 12 μm. The results of twelve resonant frequencies at mode 1 are shown in Fig. 5 presents the influence of the corrugation width. For all corrugation width, all their resonant frequencies are higher than that of flat type resonator. Furthermore, the maximum frequency occurs at width of 6 μm as shown in Fig. 4. On other hand, when the corrugation width is chosen at a half of resonator width, its resonant frequency reach maximum. At this point the resonant frequency is 901 kHz while the flat cantilever has this frequency of 746 kHz.

4. CONCLUSION

By finite element method, the corrugated structure was analyzed. This applied to both corrugated cantilever and doubly clamed beam resonator based on 3C-SiC because of its high Young's modulus and several advantageous properties. Corrugation depth and width are two crucial parameters in improving resonators. In designing, optimum corrugated resonator that has dimension of 36x12x0.5 μm^3, the corrugation has the width of 6 μm, a half of resonator's width and the depth is chosen at 0.4 μm. With this structure the resonant frequency is 1.252 MHz. Meanwhile with the same dimension flat type has frequency only 746 kHz. In this optimum design, frequency of corrugated cantilever is 68 % lager than that of flat type.

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