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Design, Modeling and Simulation of MEMS Devices on Si, SiC, and Diamond for Harsh Environment Applications

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Set of micromechanical (MEMS) test structures designed for fabrication on silicon, silicon carbide and diamond substrates has been successfully designed. A dedicated mask-set development has been carried along with numerical simulations performed with assistance of a dedicated design and modelling CoventorWare™ — toolset by Coventor. A set of sample simulations presented in this paper has been performed for specific simulation domains focused on silicon-alternative material reality to proof the usefulness of proposed substrates. The aim was to verify its applicability for MEMS design and confirm an outstanding performance of the resulting device which effectively opens a new area of interest for subsequent research and development efforts.

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1. Introduction

Latest efforts in micro-electro-mechanical system (MEMS) development aim to explore new material systems that are suited to cover fields of applications that cannot be covered satisfyingly by classical silicon substrates. The main advantage of SiC and diamond applied as a MEMS substrate in comparison with Si substrate is the intrinsic mechanical and chemical stability of those materials. SiC and diamond devices emerge from R&D as promising candidates for high-power microwave devices. The outstanding and unique combination of high level of saturated electron velocity, strong electric field breakdown, and unprecedented thermal conductivity focused the R&D interest.

Apart from the above mentioned parameters, the outstanding hardness, high Young's modulus and high chemical resistance make predestine SiC-based and diamond-based MEMS systems to operate in harsh environments. Moreover, it is possible to design and fabricate simple sensor and actuator systems embedded in majority of SiC- and diamond-based technologies even in a very early stage of technology development [1–4]. Theoretical prediction of device parameters has been achieved by means on numerical device characterization by mathematical modeling and simulation. This is the main idea of virtual prototyping useful not only in case of mature technologies but also in case of early stages of development for emerging technologies before device manufacturing. The profit is reduction of manufacturing cost and time [5, 6].

This paper is devoted to present a detailed review focused on R&D on MEMS fabricated using such experimental materials in MEMS development like SiC and diamond.

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2. Material properties

All fields of microsensor applications which cannot be achieved using standard silicon micromachining are comprised under "harsh environment applications". Such environments cover high temperature, high wear, high radiation, and/or are assisted by harsh chemicals. Outstanding properties that make SiC and diamond well suited for such applications include a wide bandgap, high hardness, high resistance to chemical etching in acids and bases, and slow oxidation rates. SiC and diamond are also of interest for RF MEMS applications, where high Young's modulus enables fabrication of mechanical resonators for unprecedented frequency range up-to GHz. Table I summarizes the properties of semiconductors (silicon, silicon carbide, diamond), which are applicable at harsh environment.

TABLE I

Selected properties of Si, SiC, and diamond for harsh environment applications [1, 3–5].

Property	Si	SiC 3C	Diamond
bandgap [eV]	1.12	2.3	5.5
max. operating temperature [°C]	130 350 (SOI)	900	1100
thermal expansion $[\frac{10^{-6}}{K^{-1}}]$	2.6	2.9	1.0
heat conductivity $[\frac{W}{cm\,K}]$	1.45	4.9	20
elastic modulus [GPa]	170	350	1000
hardness $[\frac{kg}{mm^2}]$	1000	3300	10 000

3. Modeling and simulations MEMS device for Si, SiC, and diamond and fabrication of SiMEMS — cantilever beams

For the most MEMS sensors main mechanical part is a cantilever, membrane with or without springs or a bridge. Cantilever-based sensors are devices based on the measured changes of physical quantities such as resonance frequency, amplitude and quality factor of these structures.

There are many applications for these sensors [7–9], especially if high sensitivity and reliability are required. For example, mass sensors for biological domain or high frequency oscillators and filters for telecommunication are the major applications. The sensitivity of a cantilever--based sensor is proportional to its resonant frequency so that devices with a high resonant frequency have a high resolution: this means that only a minimal amount of target molecule when attached to the surface of the cantilever can cause a large shift in its resonant frequency. There are two ways to increase the resonant frequency of a device: either by selecting appropriate materials or by changing the physical dimensions. Making the cantilever shorter is one way to increase the frequency of the device, but a cantilever with an adequate size is necessary for optical alignment (typically, a laser beam is used to detect the resonant frequency) and for the attachment of a sufficient amount of the biologically active molecules used for detection.

The cantilevers have been designed with lengths varying between 1000 μm and 4000 μm and widths of 300 μm and 700 μm (Fig. 1). The simulated concentrated load was applied at the free-end and deflection at this point was used for the calculation of the T-shaped beam stiffness.

TABLE II

Number of modes and its resonant frequencies for MEMS cantilever beams on different substrates: Si, SiC, and diamond.

Mode no.	Resonant frequency [Hz]		
	Si	SiC 3C	Diamond
1	889	1373	1750
2	5489	8497	10879
3	15259	23752	30450
4	20217	36538	48925
5	25926	40560	51983

TABLE III

Maximum MEMS cantilever displacement (on the cantilever end) and maximum mises stress in under applied load 1e-3 MPa for different substrates.

	Si	SiC 3C	Diamond
max. displacement [μm]	40	17	6.8
max. mises stress [MPa]	6.5	6.7	6.8

The fundamental resonant frequency of the fabricated devices was investigated with the use of finite element modelling (FEM) performed with the CoventorWare$^{\text{TM}}$ modelling and simulation environment [10]. The simulation results are summarized in Table II and III. In Fig. 2 sample MEMS-based device — cantilever beam fabricated in ITE on Si substrate are presented. Fabricated cantilevers will be used for dedicated accelerated ageing tests of interconnects in 3D SiP.

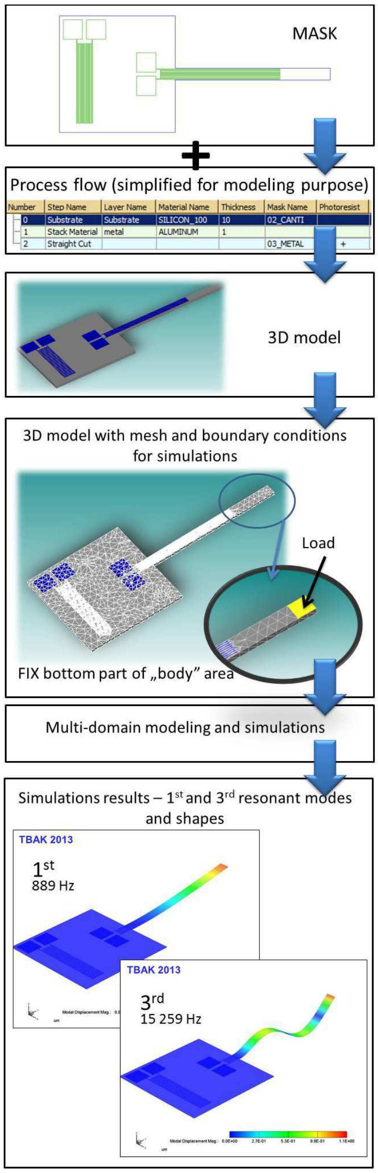

Fig. 1. Modeling and simulation: from mask set through 3D models to FEM multi-domain simulations in CoventorWare$^{\text{TM}}$ environment.

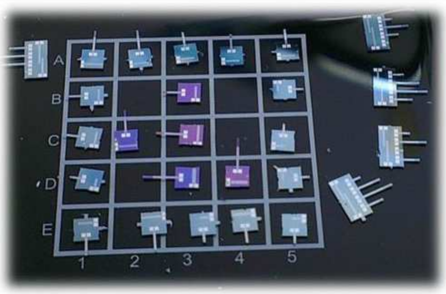

Fig. 2. Sample MEMS-based device — cantilever beam fabricated in ITE on Si substrate for accelerated ageing tests of interconnects in 3D SiP [11].

4. Conclusions

Silicon carbide and diamond reveals as a good candidate for MEMS applications, particularly when wide range of operation temperatures or harsh environments involved must be addressed. The high value of Young's modulus of these materials can be utilized in the design of high frequency resonators.

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