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A review of silicon carbide development in MEMS applications

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Abstract: Due to its desirable material properties, Silicon Carbide (SiC) has become an alternative material to replace Si for Microelectromechanical Systems (MEMS) applications in harsh environments. To promote SiC MEMS development towards future cost-effective products, main technology areas in material deposition and processes have attracted significant interest. The developments in these areas have contributed to the rapid emergence of SiC MEMS prototypes. In this paper, we give an overview of the important developments in SiC material formation and fabrication processes in recent years. Some of the most interesting state-of-the-art SiC MEMS devices are reviewed. This highlights the major progresses in SiC MEMS developed thus far. This paper also looks into the prospect of SiC MEMS drawing attention to potential issues.

Keywords: SiC; silicon carbide; MEMS; microelectromechanical systems; review; deposition; fabrication; devices; prospect.

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1 Introduction

Since its inception in the late 1960s (Nathanson et al., 1967), Microelectromechanical Systems (MEMS) have become an important area of technology combining material, mechanical, electrical, chemical, optical and fluids engineering disciplines. They allow interrelated device components to be integrated into comprehensive systems at very small scales which complete functions such as sensing and actuating. Building on the well-established techniques from the microelectronics industry over the past 50 years, MEMS have attracted considerable interest worldwide, which has led to rapid developments especially over the past decade. The total MEMS global market already exceeds $10 billion, up from $100 million only five years ago (Hensler, 2002). The primary material used in MEMS remains Si. Although Si MEMS can draw upon microfabrication techniques ready established in the microelectronics industry, due to its material properties, it is not suitable for MEMS operating in severe conditions such as high temperatures (>300°C). However, there remains an increasing demand for sensors and actuators for harsh environment applications such as devices in combustion processes, gas turbine control and oil industry, which has stimulated the search for alternatives to Si. As a result, Silicon Carbide (SiC) has been recognised as an excellent candidate for microsensor and microactuator applications in harsh environments due to its unique properties which include high hardness and wear resistivity, good thermal conductivity and chemical inertness. Table 1 shows the basic material properties of SiC in comparison to those of Si and GaAs conventional semiconductors.

The field of SiC MEMS is still in its infancy and occupies a niche market. Capturing a large percentage of the total MEMS market requires substantial research to address challenges in many aspects in relation to SiC MEMS developments. Since Cree Research Inc. became the first supplier of SiC substrates in 1987, single crystal SiC wafers have been commercially available. However, from a product development point of view, the development of larger-area substrates at lower costs is still required. In comparison, large-area Si wafers can already be produced with high volume and at low unit cost. In recent years, epitaxial grown single and polycrystalline SiC layers on Si or SOI wafers have shown advantages in the realisation of cost-effective SiC MEMS devices. This has stimulated research on SiC layer deposition and characterisation. Furthermore, there is limited knowledge in many essential areas of SiC MEMS such as etching, doping, oxidation and contact metallisation. Therefore, research activity thus far has focused on these areas with a view to the development of efficient micromachining processes. With the development in SiC material and fabrication processes, new SiC MEMS device prototypes have been rapidly emerging which could potentially have a strong impact to the overall MEMS market.

Table 1 SiC material properties in comparison to those of Si and GaAs

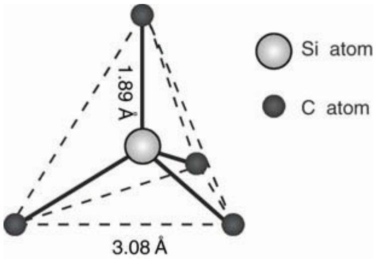
Properties	*3C-SiC (6H-SiC)*	*Si*	*GaAs*
Lattice constant (Å)	4.36 (a_0: 3.08; C_0: 15.12)	5.43	5.65325
Band gap (eV)	2.36 (3)	1.12	1.4
Density (g/cm^3)	3.21	2.33	5.32
Melting point (°C)	Sublimes at $T > 3100$	1410	1240
Thermal conductivity (W/cm K)	4.9	1.5	0.55
Linear thermal expansion coeff. (10^{-6} K^{-1})	2.9 (4.2)	2.6	5.73
Young's modulus (GPa)	392–694	130–185	85.5
Physical stability	Excellent	Good	Fair
Electron mobility (cm^2/V s)	1000 (400)	1500	8500
Hole mobility (cm^2/V s)	40 (50)	450	400
Breakdown field (10^6 V/cm)	4	0.3	0.4

Focusing on recent progresses, this paper gives a brief overview of SiC MEMS development in terms of achievements and challenges. In the remainder of this paper, Chemical Vapour Deposition (CVD) as a main deposition technique for SiC MEMS is reviewed in Section 2. Microfabrication methods associated with SiC MEMS are summarised in Section 3. The key microfabrication step of dry etching of SiC and its recent development are set out in this section. The wide range of applications and reported examples of up-to-date SiC MEMS devices are given in Section 4. In particular, SiC resonators and sensors as well as SiC coated MEMS are described. Finally, Section 5 looks to the future of SiC MEMS highlighting issues still requiring attention.

2 Chemical vapour deposition of SiC

SiC is the only known binary compound of Si and C and exhibits a one-dimensional polymorphism called polytypism. A large number of SiC polytypes exist, which are distinguished by differences in the stacking sequence of the identical planes of Si and C atoms. In the SiC polytypes, the basic structural unit consists of a primarily covalently bonded (88% covalent and 12% ionic) tetrahedron of four C atoms with a Si atom at the centre (or four Si atoms with a C atom at the centre) (Park, 1998) as shown in Figure 1. Main SiC polytypes that are commercially available and relevant to SiC device applications are 4H-, 6H- and 3C-SiC. Hexagonal 4H- and 6H-SiC bulk substrates have been used to fabricate pressure (Okojie et al., 1998) and acceleration (Okojie et al., 2001) sensors through bulk micromachining processes. 3C-SiC is the only SiC polytype that can be synthesised on Si substrates which enables deposition on large-area substrates. Therefore, in the last few years, 3C-SiC as the dominant polytype for MEMS applications has attracted most of the attention. In addition, due to the preservation of many desirable properties, amorphous SiC (a-SiC) is a particularly attractive material for devices where low deposition temperature is necessary. Among the available techniques developed thus far, CVD techniques are widely used in 3C- and a-SiC formation and are reviewed in the following sections.

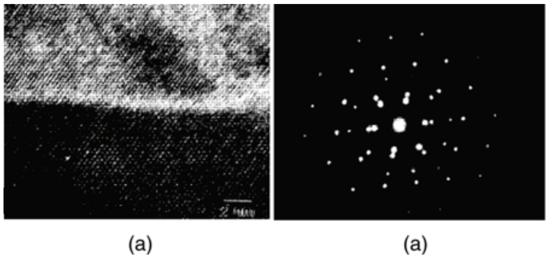
Figure 1 A SiC unit cell



2.1 Atmospheric pressure chemical vapour deposition

Atmospheric Pressure Chemical Vapour Deposition (APCVD) was one of the first techniques developed to deposit SiC. A typical APCVD reactor is comprised of a cooled wall chamber, reactive gas inlet, exhaust port, a substrate susceptor centrally positioned in the reactor chamber and heating coils (Zorman et al., 2006). During the deposition, a carbonisation process (Nishino et al., 1983; Powell et al., 1987; Zorman et al., 1995) is initially applied to a clean Si surface, followed by SiC growth using Si and C containing precursors. SiC growth rate up to several microns per hour can be achieved with the potential to be doped into *N* and *P* types. An APCVD system is relatively simple and easy-to-setup due to the incorporation with few temperature sensitive components. Both epitaxial and polycrystalline 3C-SiC can be deposited by APCVD. It is particularly advantageous for SiC epitaxy, where higher temperatures (1300°C) are typically required for single crystalline SiC grown on Si substrates. Due to mismatches in thermal expansion coefficients and lattice constants, residual stress often exists in these epitaxial layers. Figure 2 shows a typical TEM results obtained from an epitaxial 3C-SiC film by APCVD. The deposited films are particularly suitable for single crystalline 3C-SiC MEMS structures fabricated through Si bulk micromachining such as membranes (Mitchell et al., 2003) and piezoresistive pressure sensors (Zorman et al., 2006).

Figure 2 (a) High-resolution TEM image of the SiC/Si interface and (b) cross-sectional TEM diffraction pattern of the SiC/Si interface



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2.2 Low pressure chemical vapour deposition

A typical Low Pressure Chemical Vapour Deposition (LPCVD) system usually consists of a reactor chamber, gas inlet, vacuum system and heating element using induction, resistive or IR lamp heating. Although film growth rate is much lower than that in APCVD processes, more substrates can generally be accommodated in LPCVD especially when resistive heating is used. Zorman et al. (2002) recently reported a unique LPCVD furnace capable of holding up to 150 mm-diameter substrates. Due to the vacuum system involved and lower chamber pressure, compared to APCVD, LPCVD allows exploiting more varieties of precursors as well as reducing the incorporation of impurities in the deposited films. Therefore, in general, the process generates higher quality SiC films with much better uniformity across large substrate areas. Epitaxial 3C-SiC film has also been grown on Si wafers by LPCVD and its membrane structures (Krotz et al., 1995) showed much better performance at higher pressure and elevated temperatures comparing with their Si counterparts. In recent years, LPCVD has become a leading technique for polycrystalline 3C-SiC films which can be deposited on various substrates including SiO_2 and Si_3N_4 and thus introduce great flexibility in SiC MEMS design and fabrication. As an important factor affecting MEMS performance, residual stress in the films from LPCVD can be controlled by the deposition pressures. Doping can also be achieved in situ by adding dopants into the feed gas. Thus far, a number of precursors have been explored for SiC LPCVD processes (Boo et al., 2000; Chen et al., 2000; Clavaguera-Mora et al., 1997; Hurtos and Rodriguez-Viejo, 2000; Lee et al., 2001). In particular, Stoldt et al. (2001, 2002) have developed a low temperature (800–1000°C) process to deposit polycrystalline 3C-SiC films for MEMS applications utilising 1,3-Disilabutane (DSB) as precursor. Controlled nitrogen doping is also demonstrated (Wijesundara et al., 2002) at 850°C by the addition of NH_3 to the feed gas, as shown in Figure 3. By varying Dichlorosilane (DCS) and 1,3-DSB fractions in the inlet gas mixture, this group also reported (Roper et al., 2006) that the residual stress and strain gradient of polycrystalline SiC films can be tuned, which is demonstrated by the bending of the subsequently fabricated cantilever beams in Figure 4.

Figure 3 The resistivity and the conductivity of the cubic-SiC films as a function of percentage of NH_3 gas in the feed gas

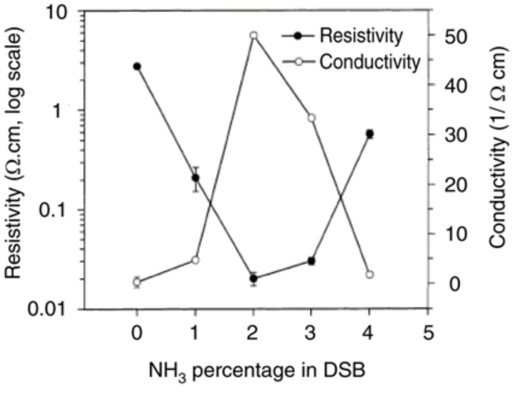

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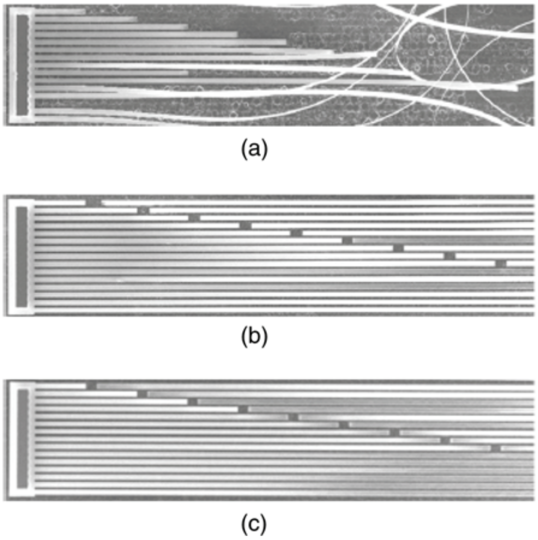
Figure 4 SEM of the SiC cantilever beam array for films deposited with (a) no DCS, (b) 20 sccm DCS and (c) 40 sccm DCS



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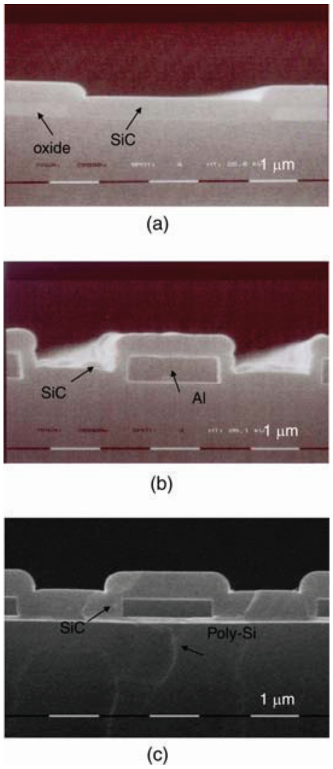
2.3 Plasma enhanced chemical vapour deposition

All the above mentioned CVD methods require reasonably high temperatures. In contrast, Plasma Enhanced Chemical Vapour Deposition (PECVD) allows SiC films to be deposited at much lower temperatures (200–400°C). Commercially available PECVD systems can be utilised for the processes which is beneficial from future mass production point of view. The low deposition temperatures also suggest its potential suitability for IC compatible MEMS processing. Many Si and C containing gas precursors such as SiH_4 and CH_4 (Flannery et al., 1998; Sarro et al., 1998) as well as liquid source such as $C_6H_{18}Si_2$ (hexamethyldisilane) (Klumpp et al., 1994) have been used to form a-SiC by PECVD. The as-deposited SiC films are amorphous and post-deposition annealing is required for crystallisation. The deposited a-SiC is usually employed as a coating material for various MEMS component (Flannery et al., 1998). Systematic research carried out by Sarro et al. (1998) has demonstrated that, using a high throughput PECVD system, it possible to control the stress in the deposited films by altering deposition parameters such as pressure and gas flow ratio. Both doped and undoped SiC can be obtained by PECVD. Due to the low temperature in the PECVD processes, it is feasible to deposit SiC on a variety of materials such as aluminium which is not possible in the APCVD and LPCVD processes. Figure 5 shows that using the same PECVD conditions, a-SiC can be deposited on patterned oxide, aluminium and polysilicon with reasonable conformal coverage.

Figure 5 SEM micrographs illustrating the step coverage of PECVD SiC deposited on patterned (a) oxide, (b) aluminium and (c) polysilicon (see online version for colours)



Source: Pictures courtesy of Sarro (2000). DIMES, Delft University of Technology, The Netherlands.

3 Fabrication processes for SiC MEMS

Effective fabrication routes play key roles in the realisation of reliable MEMS. The advanced physical and chemical properties of SiC form the cornerstone for SiC MEMS as well as the microfabrication challenges. Therefore, unlike well-established Si microfabrication processes, there is still a strong requirement of efficient and cost-effective micromachining techniques for SiC MEMS. Bulk and surface micromachining are the main fabrication routes for MEMS in general (Madou, 1997; Wise, 1998). Thus, their developments towards SiC MEMS are briefly reviewed in the subsections.

3.1 Bulk micromachining

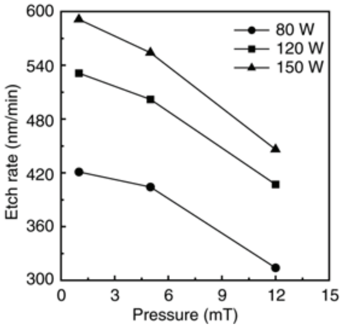
It is generally difficult to perform bulk micromachining of SiC substrates because standard Si bulk micromachining techniques are not effective in SiC etching. Powerful techniques such as laser ablation (Dong et al., 2003) and focused ion beam sputtering (Bischoff et al., 2001) have been utilised for this purpose. A laser assisted photoelectrochemical etching technique has also been developed to fabricate a 6H-SiC pressure sensor (Okojie et al., 1998). The ability to deposit 3C-SiC on Si substrates has made many devices possible by employing conventional Si bulk micromachining. In these processes, SiC has high etch resistance in most commonly used anisotropic etchants to remove the bulk silicon (KOH, TMAH or EDP solutions). Therefore, using bulk Si anisotropic etching as the final releasing step from the back of the wafer, a multitude of 3C-SiC structures, ranging from diaphragms, cantilever beams and torsional structures for mechanical property studies, to transmission windows for optical studies (Mehregany et al., 1997) have been realised. Alternatively, bulk Si anisotropic etching from the front of the wafer can also be exploited to achieve free standing SiC microstructures. In particular, when the starting material is thin SiC layer grown on top of Si wafer, a one-step process has been developed (Jiang et al., 2003a) to fabricate straight SiC resonators. In this case, using patterned SiO_2 as etch mask, inductive coupled plasma using SF_6/O_2 gas mixture etches the SiC anisotropically followed by the bulk isotropic etching of the Si underneath from the front of the wafers which consequently frees the SiC beams. In addition, SiC can also be deposited into a Si mould precreated by deep reactive ion etching (Rajan et al., 1998), subsequently the MEMS devices can be realised by chemical mechanical polishing and release of the SiC structures by dissolving the Si mould.

3.2 *Surface micromachining*

Thin films of polycrystalline and amorphous SiC can be deposited on a variety of substrates which include thin layers of polySi, SiO_2 and Si_3N_4 on top of Si wafers. Using these multilayered structures, devices with thin SiC as structural material and polySi or SiO_2 as sacrificial layers can be fabricated by surface micromachining processes. As the only practical way to pattern SiC for MEMS applications (Xie et al., 1995), plasma-based dry etching is a key process in SiC surface micromachining. Recent developments in this area are reviewed as follows.

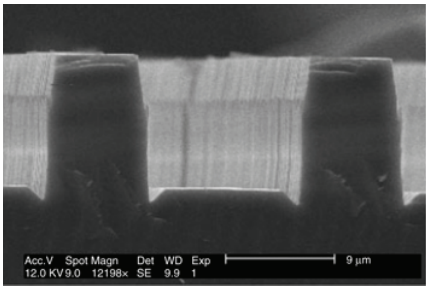
Fluorine-based gas mixtures have been shown to be the most effective gas for SiC etching in terms of high etch rate. The F species in the plasma can react with both Si and C to form volatile compounds as reaction products. Commonly, SF_6 and O_2 gas mixtures are used because the optimum amount of O_2 addition provides another pathway for volatilising C in the forms of CO, CO_2 (Flamm et al., 1981; Jiang et al., 2003b) and thereby increases etch rates. SiC etch rate of 1.05 μm/min (Khan et al., 2001) has been achieved in an inductively coupled plasma reactor using SF_6 and O_2 gas mixtures. However, obtainable SiC etch rates strongly depend on the plasma conditions used such as pressure, flow rate, chuck power, etc. Figure 6 (Jiang et al., 2003b) shows the SiC etch rate as a function of pressure at different chuck powers in an inductively coupled plasma chamber. Due to an ion induced etching mechanism, anisotropic etch profiles are often achieved, as shown in Figure 7 (Plank et al., 2003). The etch selectivities of SiC over metal mask materials such as Ni and Al are about 20 and 7, respectively, which are much higher than those of SiC over photoresists or dielectrics (Pearton, 2006). It is also worth mentioning here that chlorinated plasma has also been investigated (Jiang et al., 2004; Khan et al., 2001) because it induces little surface damage, although the etch rates are much lower.

Figure 6 SiC etch rate versus pressure at chuck power of 80, 120 and 150 W, respectively SF_6 flow rate = 40 sccm and O_2 flow rate = 10 sccm



Source: Jiang et al. (2003b).

Figure 7 Anisotropic SiC etch profile



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4 SiC in MEMS device applications

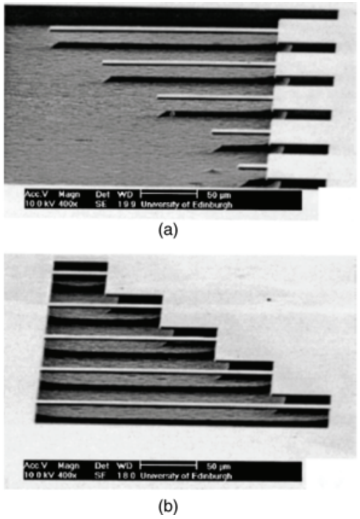
The advancement of the material deposition techniques and fabrication processes for SiC has enabled the successful realisation of numerous SiC MEMS devices over the years. A few papers (Mehregany and Zorman, 1999; Sarro, 2000) and books (Cheung, 2006; Park, 1998) have given comprehensive and timely overviews in the past on the relevant development. This section focuses on the recent progress of some specific SiC-based MEMS devices. Since it is difficult to cover every device reported so far, the review focuses on some interesting development in application areas of SiC as resonators, sensors and MEMS coatings.

4.1 SiC resonators

SiC has larger ratio between Young's modulus and density (E/ρ), which results in higher resonant frequencies with better quality factors for beam structures compared to their Si and GaAs counterparts (Yang et al., 2001). This is particularly beneficial for micromechanical resonators to be used as frequency filtering in high-performance communication transceivers (Nguyen, 1997), oscillators and high sensitivity sensing.

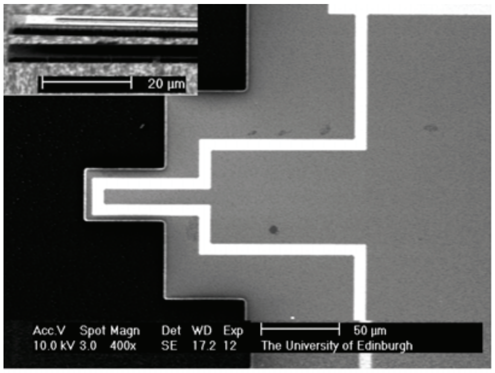
SiC lateral resonators have been fabricated by surface micromachining and packaged for operations in high-temperatures environments (Roy et al., 2002). Recently, Jiang et al. have described the development of SiC resonator structures with mechanical (Jiang et al., 2003a), electrostatic (Jiang et al., 2005) and electrothermal actuations (Jiang et al., 2006), respectively. Simple cantilever and bridge beams have been designed and fabricated by bulk and surface micromachining processes. The basic structures are shown in Figure 8. Through mechanical actuation, the fundamental resonance frequencies (f_0) have been identified to be between 120 KHz and 5 MHz depending on the beam geometry (Jiang et al., 2003a). A thin NiCr electrode is included on top of the beams and forms ohmic contact with SiC. The resonators can then be electrostatically excited by applying a sinusoidal ac voltage (V_{ac}) at f_0 and $f_0/2$ with a dc component (V_{dc}) between the top NiCr/SiC and bottom bulk Si electrodes. The amplitude of the fundamental resonant peaks has been found to have a linear relation with the applied V_{ac} and V_{dc}, respectively (Jiang et al., 2005). Furthermore, for the first time, SiC resonators with electrothermal actuation have also been reported. Electrothermal actuation is especially suitable for device applications requiring large displacement and high contact force. NiCr heating elements were patterned on top of the SiC beams (Figure 9) and electrothermal actuation was achieved by applying a combination of V_{ac} and V_{dc}. It is also been found that, during electrothermal actuation, f_0 can be tuned by the applied V_{dc} (Figure 10) which could be potentially advantageous for the post-package fine tuning of the SiC resonators (Jiang et al., 2006). Lastly, the development of SiC nanomechanical resonators have been reported as a step towards SiC Nanoelectromechanical Systems (NEMS) devices (Yang et al., 2001). This could be beneficial for the development of future generations of RF devices and ultrasensitive sensors. It is worth noting that attention should be paid in NEMS because scale effects are likely to enter into the design and affect material issues within the devices (Spearing, 2000).

Figure 8 SEM images of a group of free standing (a) cantilever beams with lengths of 25, 50,100, 150, 200 µm, respectively and (b) bridges with lengths of 50, 100, 150, 200, 250 µm, respectively. All the beams are 15 µm wide and nominally 2 µm thick



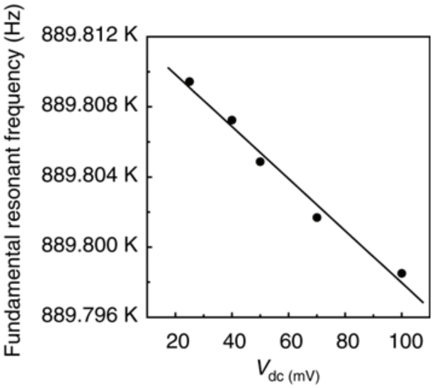
Source: Jiang et al. (2003a).

Figure 9 SEM micrographs of the fabricated NiCr/polySiC cantilever. The inset shows the side view



Source: Jiang et al. (2005).

Figure 10 The shift of the fundamental resonance frequency versus input V_{dc} (V_{ac} = 48 mV$_{pp}$) for an electrothermally actuated NiCr/polySiC cantilever

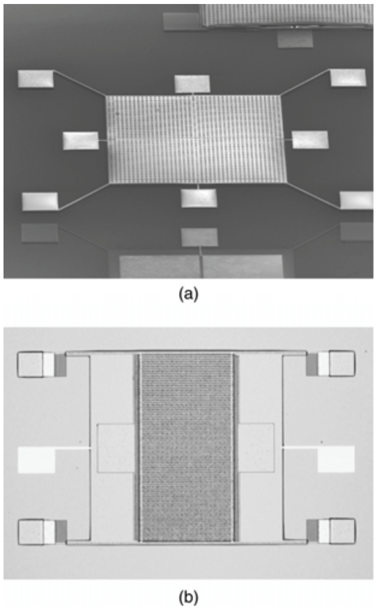


Source: Jiang et al. (2006).

4.2 SiC sensors

Advanced SiC sensor systems have been developed to detect pressure, acceleration, chemicals and even radiation. Among these, SiC pressure sensor application is one of the main application areas of SiC MEMS. It is particularly suitable for applications in high temperature, high pressure and vibration environments such as pressure sensors used in oil industry. A multitude of SiC pressure sensors have been reported (Pakula et al., 2003a,b; Zappe et al., 2001; Ziermann et al., 1999) over the years. Very recent research from Wu et al. demonstrated the development of diaphragm type pressure sensors based on polySiC and 3C-SiC piezoresistors (Wu et al., 2006). PolySiC diaphragm was used for the former with the polySiC piezoresistors doped by introducing dopant gas PH_3 during APCVD, while Si diaphragm was employed for the latter with the 3C-SiC unintentionally nitrogen doped during APCVD. Although the gauge factor of the SiC piezoresistors was compromised with increasing operating temperature, sensing capabilities up to 400°C have been demonstrated. Another important area of technology is SiC accelerometers which are particularly attractive for detecting high-g acceleration at elevated temperatures such as in aeroplane engine, military and space applications (Atwell et al., 2003; Okojie et al., 2001). Recent findings from Pakula and French have demonstrated a CMOS compatible 3D SiC capacitive accelerometer with both vertical and lateral accelerometers fabricated in the same process using PECVD SiC (Pakula et al., 2003a,b). The fully released structures are shown in Figure 11. Furthermore, SiC chemical sensors have also been investigated based on components such as SiC Schottky diode (Baranzahi et al., 1997) and microhotplate structures (Solzbacher et al., 2001). Using these devices, a combustion monitoring gas sensors for operation up to 700°C was obtained (Baranzahi et al., 1997). Porous SiC has also been used to fabricate relative humidity sensors (Connolly et al., 2002). Finally, Strokan et al. has demonstrated the possibility to use SiC-based structures to detect alpha particles and weak ionisation radiation (Strokan et al., 2003).

Figure 11 (a) SEM photo of fully processed vertical accelerometer and (b) processed lateral accelerometer



Source: Pictures courtesy of Pakula et al. (2003). DIMES, Delft University of Technology, The Netherlands.

4.3 SiC coated MEMS

One of the reliability issues relating to Si MEMS is unwanted wear and adhesion. Being a more robust material SiC shows superior tribological properties over Si. Therefore, SiC cannot only be used as a structural material to realise reliable micromechanical devices such as micromotors (Yasseen et al., 2000), it can also be utilised as a coating material for Si MEMS aiming at better reliability and enhancement of device lifetime. For example, compared with similar Si devices without coating, a SiC coated fuel atomiser presented an improved erosion resistance for long term use and resistance to fatigue in high-temperature conditions (Rajan et al., 1998, 1999). Ashurst et al. have reported a comparative wear study for released Si microstructures to be coated with oxidise, antiadhesion and SiC coatings, respectively (Ashurst et al., 2004). Low temperature (800°C) deposition from DSB precursor has been used to form a thin conformal SiC coating. Their results suggest that SiC coating provides exceptional wear resistance and significant reduction in friction on the microscale. Their findings are consistent with earlier results where 3C-SiC films showed low coefficient of friction and superior scratch/wear resistance when compared to Si materials (Sundararajan, 1998). Recent results from the same group (Gao et al., 2006) also suggests that, using SiC as a substrate material significantly reduces the in-use stiction of Si MEMS structures.

5 Summary and prospect

Due to its advanced material properties, SiC has become one of the prime candidates for MEMS operating in sever conditions. In the last few years, enormous amount of research worldwide has been conducted towards the advancements in SiC material deposition, microfabrication and realisation of applicable device prototypes. Recent progress in these areas of technology has further accelerated the advancements which are briefly reviewed in this paper. In particular, CVD techniques can now provide single crystalline, polycrystalline and amorphous SiC with good material quality and high throughput; essential micromachining techniques continue to progress towards better efficiency. The developments in these areas significantly contributed to the embodiment of the SiC MEMS devices with a range of new prototypes rapid emerging.

Despite these exciting accomplishments, from commercialisation point of view, the field of SiC is still in its infancy. However, companies such as FLX micro have started to introduce a commercialised SiC foundry service. To promote the realisation of cost-effective SiC MEMS, many relevant aspects still require attention. For instance, to reduce the overall cost, more efficient material growth and micromachining techniques are required. Development of IC compatible processes are advantageous for MEMS in general, effective techniques would clearly be beneficial for SiC MEMS. Furthermore, for applications in harsh environments, it is particularly important to realise the integration between SiC MEMS and electronics. Thus, the interrelated field of SiC electronics has direct impact on its MEMS counterpart. Although there are challenges and issues that still need to be addressed before we see SiC MEMS produced with high volume and low unit cost, the potential of SiC MEMS has been identified. With some technical breakthroughs already in the horizon, its real potential could be realised in the near future.

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