A REVIEW ON LASER ASSISTED DEPOSITION AND MICRO-ETCHING OF SILICON CARBIDE (SiC) COATING FOR MEMS DEVICE APPLICATIONS

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Abstract

Single crystal silicon carbide (SiC) material is highly suitable for the development of Micro Electro Mechanical Systems (MEMS) devices.SiC are highly suitable for high-temperature application due to its mechanical robustness, chemical inertness and electrical stability at elevated temperatures. Wide varieties of reports are published on the convention Chemical Vapour Depostion (CVD) and chemical etching techniques based Micro-Fabrication and micro etching of SiC in particular for MEMS device. But however laser based SiC micro fabrication and micro-etching have their own advantages as compared to the conventional system. This paper highly focuses on how well the laser based micro fabrication and micro –etching can be tailored for the development of SiC based MEMS device.

Key words: MEMS, Laser based coating, micro-etching, sensors for high temperature applications.

I. INTRODUCTION

Over the past decade, *Micro-Electro Mechanical Systems (MEMS)* technology has evolved from a *niche* technology into an important mainstream technology for a wide range of applications including micro-sensors and actuators(1-3). MEMS can sense their environment and have capability to react to changes in the environment. Among the various materials used for such applications, Silicon has been the preferred choice. But the high demand of sensors capable of operating at a temperature well above 300°C, often in severe environments, motivated the search for alternative materials. Silicon Carbide (SiC) possesses excellent material properties, wider band gap, higher breakdown voltage, much higher heat conductivity and melting temperature than Silicon. This makes SiC a promising material for high temperature ($>$600°C) MEMS sensors (pressure, temperature, gas and optical) and actuators. Among all MEMS based devices, the demand of SiC based pressure sensors is growing in numerous industries including transportation (automobile, diesel and aerospace), energy (power generation, petrochemical refineries and oil & gas industries), and environmental (HVAC systems). SiC exists in a number of different forms, but only three polytypes (3C-SiC, 4H-SiC, and 6H-SiC) could be grown in single crystalline conforming suitability for microelectronics and MEMS industries(4-6). Therefore, the performance and reliability of SiC MEMS devices depend on the fabrication techniques(7-8). The MEMS based fabrication techniques basically include the material deposition and material etching. A variety of techniques are used to grow single and polycrystalline forms of SiC thin films, including atmospheric pressure CVD (APCVD), sputtering, metal-organic CVD, atomic layer deposition (ALD) etc. Though CVD is a relatively old and powerful method for producing crystalline SiC(9-12), it has limitations as it needs high processing temperature and the possibility of contamination is quite high. In the case of micro etching, conventional fabrication methods, such as reactive ion etching (RIE), electron cyclotron resonance (ECR), deep reactive ion etching (DRIE) do not reach the goal easily due to high hardness and chemical stability of SiC (13-16). Moreover, these methods have limitations due to poor etch selectivity and slow etching rate preventing large volume production of SiC MEMS devices at low cost(17-20). These limitations can be overcome using laser micro-fabrication and micro-etching techniques.

Laser micro-fabrication and micro-etching has a great potential as a MEMS fabrication technique owing to its material flexibility and 3D capabilities. Due to precise control on laser variables, such as - wavelength, pulse width, repetition rate, laser fluence (energy per unit area) etc., high-quality microstructures can be fabricated easily in shorter time(21,22). This review paper presents a brief overview on the functionality of SiC as a MEMS device and requirements for different micro fabrication and micro-etching techniques. The limitations of conventional micro-fabrication and micro etching techniques and how these limitations can be overcome by Laser assisted micro-fabrication on and micro etching of SiC for MEMS application is also discussed.

II. SiC FOR MEMS BASED STRUCTURES

Silicon Carbide, also known as carborandum, is a compound of silicon and carbon with a chemical formula of SiC. SiC has polytypes consisting of 50% carbon atoms covalently bonded with 50% silicon atoms having its own distinct set of electronic properties. Though more than 100 polytypes are known, only a few are commonly grown in a reproducible form and acceptable for semiconductor applications. The three most commonly used polytypes are 3C, 6H and 4H. The 3C polytypes, also known as beta-SiC (or $\beta - \text{SiC}$), exhibits cubic structure, crystallizes in a ZnS-type structure and grows epitaxial on silicon substrates. It requires much lower substrate temperature (1500°C or less) as compared to others during CVD. In contrast, 6H-SiC and 4H-SiC, both in hexagonal, alpha form, do not grow on other substrates except 6H-SiC and 4H-SiC which requires higher temperatures (up to 2000°C). All these three polytypes are relevant for MEMS applications. Their elastic compliance and constants can be found elsewhere: 3C–SiC(24-26), 4H–SiC(27-33) and 6H–SiC(34-38). The fracture toughness of MEMS-relevant thin films and structures was reported to be 3–4 times higher than for silicon (39). For the hardness, no reliable data are available. The reported values of Knoop hardness for 3C (40) and 6H–SiC(40-41) are $2480\ \text{kg mm}^{-2}$ and $1830\ \text{kg mm}^{-2}$ respectively, while the micro-hardness for 6H–SiC is 22.9 GPa (42) and 25 GPa(43).The values for Young's modulus reported in the literature are in the range of 380 to 700 GPa for 3C–SiC. The anisotropy in cubic crystals is given by $2C44/(C11 - C12)$(44) and the reported values yields an anisotropy factor between 1.6 and 2.2 (45-48) indicating Young's modulus is expected to be anisotropic. Consequently, Young's modulus for polycrystalline SiC films is lower than that for single crystalline SiC. These properties make the different structures of SiC for different MEMS application as listed in Table 1.

Table 1. Properties of SiC Structures

Different SiC structures	Structure	Bandgap (eV)	Thermal conductivity (1/K)	Density (g/cm^2)	Melting point (K)
3C-SiC	T^2_d-F43m	2.4	3.6	3.21	3103
4H-SiC	C^4_{6v}-P6$_3$mc	3.2	4.9	3.21	3103
6H-SiC	C^4_{6v}-P6$_3$mc	3.0	4.9	3.21	3103

A. Pressure Sensors

6H-SiC-based pressure sensor, can exhibit a full-scale output of 40.66 mV at 1000 psi and 25°C, decreasing to 20.33 mV at 500°C, is reported (49). The sensor was tested in the temperature range between $25 - 400$°C and at pressures up to 500 kPa. The sensor showed a linear output voltage over the pressure range and a temperature coefficient of sensitivity of 0.16%/°C at 400°C.

B. Optoelectronics and Sensors

The wide bandgap of 6H-SiC is also useful for realizing low photodiode dark currents, as well as sensors that are blind to undesired near-IR wavelengths produced by heat and solar radiation. Commercial SiC-based UV flame sensors, based on epitaxially grown, dry-etch, mesa-isolated 6H-SiC p-n junction diodes, have successfully reduced harmful pollution emissions from gas-fired ground-based turbines used in electrical power generation systems(50).

C. Lateral Resonant Devices

Lateral resonant devices are basic to surface micromachining and are used extensively as building blocks for a variety of sensor and actuator implementations. Si based lateral resonant devices, however, are not suitable for operation in high temperature environments. The first reported SiC-based surface-micro machined lateral resonant devices were fabricated using poly-SiC films deposited on polysilicon sacrificial layers(51).

D. Temperature Sensors

A poly-SiC thin-film thermistor on an alumina substrate was first reported in 1990 (52). The sensor was fabricated from RF-sputter-deposited SiC, using sintered SiC as a target. The substrate was maintained at a deposition temperature of 650°C. The device was tested at temperatures from 0 to 500°C.The results showed that the thermistor constant (B) increased linearly with temperature over the entire temperature range. Compared with conventional metal–oxide thermistors, the temperature coefficient of resistance (TCR) for the SiC devices decreased slowly with increasing temperature. Additionally, the sensor exhibited good thermal stability and a rapid thermal response with a resistance change of only 5% after a continuous test at 500°C for 1000 h (53-55).

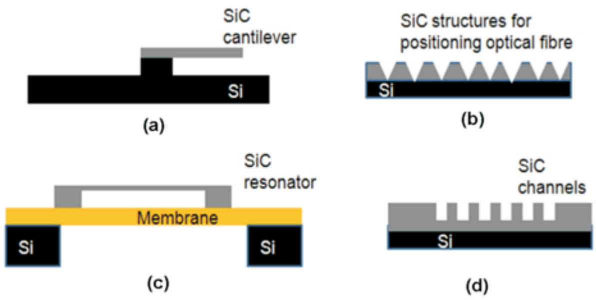

Fig. 1. Different structures of SiC based MEMS device

Figure 1 shows the different structures of SiC designed for MEMS device application. Developing these structures requires a high precise fabrication technique and micro etching technique.

III. MICRO FABRICATION AND MICRO-ETCHING OF SiC

A. Conventional Micro-fabrications techniques

Atmospheric pressure CVD (APCVD), sputtering, metal-organic CVD, atomic layer epitaxy, molecular beam epitaxy, are the current techniques used to grow single, amorphous and polycrystalline forms of SiC bulk and thin films(56-60). Conventional silicon bulk micromachining techniques can be used for fabricating single-crystal, poly and amorphous SiC with some difficulty. Single crystal and poly-SiC layers between a few microns and several tens have been used for BMM structures. Their mechanical properties can be adjusted during or after growth, so to obtained low stress structures.

Amorphous SiC films are generally thinner as stress is more difficult to control. Therefore, they are often used it in sandwich configurations together with silicon oxide, nitride or poly-silicon. Single-crystal SiC films are grown directly on single-crystal silicon. Therefore, no conventional surface micromachining is possible with crystalline layers on silicon. Poly-crystalline and amorphous SiC layers, on the other hand, can be grown on various substrates and are suitable for surface micromachining. Poly-SiC is generally grown on a poly-Si layer or deposited on oxide layers. The SiC is the mechanical or structural layer while the poly-Si or the oxide is used as sacrificial layer. When poly-Si is used as sacrificial layer, KOH or TMAH are used to release the SiC microstructures so that the oxide can protect the underlying silicon during the final sacrificial etch. If the oxide is used as sacrificial layer, HF based solutions are used, just as in conventional silicon surface micromachining. No protection of the mechanical layer is required since SiC is HF resistant. Multi-layer structures are also possible. If an oxide layer is grown under the poly-Si layer, the oxide could be used as sacrificial layer and both poly-Si and poly-SiC can be used as mechanical layers (61-66). As SiC is grown on Si wafers and as plasma etching of both Si and SiC is possible in the same fluorine based chemistry, it is possible to apply DRIE to the SiC/Si system as well.

However in the above techniques, the chemical stability of the SiC makes it difficult to perform micro-fabrication process such as etching. Reactive ion etching, photochemical etching, inductively coupled plasma and electron cyclotron resonance methods are used to etch, but at very low rates. For example, a maximum etch rate of 0.97 %m/min was achieved of SiC to Si and SiO_2 is poor. Micro-fabrication of MEMS device or via holes for high frequency electronics devices require deep etching (up to 400%m) and, consequently, high etch rate processes are desired. These limitations can be completely overcome using pulsed laser micro-fabrication techniques to improve the etch rate as well as feature quality in applications like micro motors, resonators, micro gripper etc. the demands of industrial manufacturing for fast, precise Micro-Fabrication are better met by the robust, reliable, high repetition rate and high power Nano/Femto and Pico- second lasers(67-69).

B. Laser based micro-fabrication (SiC Deposition)

Pulsed laser deposition (PLD) has found wide attention over the past decade for its ease of use and success in depositing thin films of complex stoichiometry materials. Figure 2 presents the schematic layout of PLD deposition of SiC on silicon substrate. In laser ablation, high-energy laser pulses are used to evaporate the matter from the surface of SiC target in such a way that the stoichiometry of the material is faithfully preserved during the interaction. A supersonic jet of particles (plume) is ejected normal to the target surface. The plume, similar to the rocket exhaust, expands away from the target with a strong forward-directed velocity distribution of the different particles. The species condense on the substrate placed opposite to the target. The ablation process takes place in a vacuum chamber - either in vacuum or in the presence of some background gas, depending upon the applications. The major parameters involved in this process are (70-74)

1. Type of laser, pulse width (nanosecond, picosecond and femtosecond)
2. Laser fluence (i.e. the energy per unit of area) and wavelength
3. Structural and chemical composition of the target material
4. Chamber pressure and the chemical composition of the buffer gas
5. Substrate temperature and the distance between the target and the substrate.

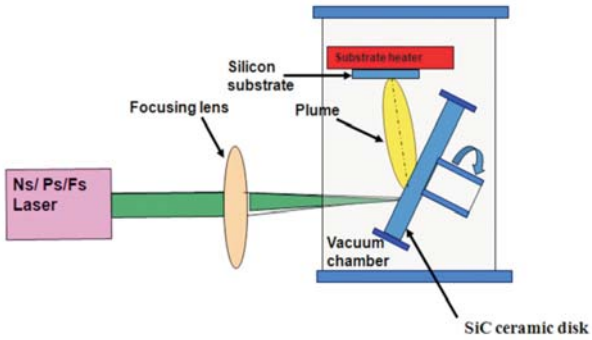

Fig. 2. Schematic sketch of Pulsed Laser Deposition.

The laser ablation mechanisms involve many complex physical phenomena such as collision, thermal, and electronic excitation, exfoliation and hydrodynamics. The phenomenon's are highly governed by the pulse width of the laser used. Ablation of targets with materials with nanosecond/femtosecond lasers has their own influence in the deposition of the SiC. These PLD techniques can be appropriately tailored for the

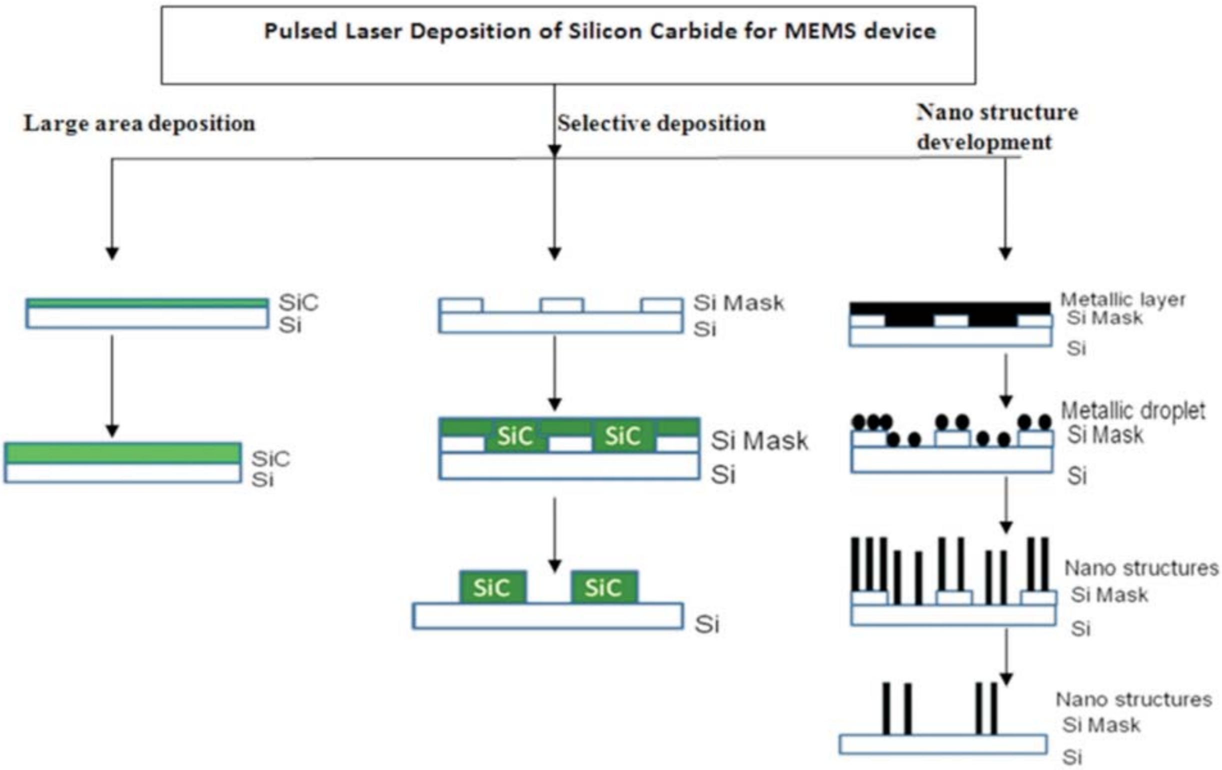

Fig. 3. Classification on PLD based micro-fabrication for development of SiC based devices.

growth process of SiC for different MEMS device development. PLD of SiC for MEMS applications are classified in to three based on the MEMS device development requirement. 1) Large are thin film deposition 2) selective deposition 3) positioning of nanostructures as shown in Figure 3.

In PLD technique, large area deposition is performed by moving the substrate or by rotating the target with a particular angle. CVD has its own limitations on selective area deposition, which can be overcome with PLD. With nanosecond laser 3C-SiC was deposited on Silicon (100) substrates using PLD. The deposition was performed at different temperature conditions ranging from 550 to 700°C. Thin SiC films were grown on (100) Si and Silicon (111) substrates. The different parametric condition including the laser repetition rate, and laser fluence were optimised for efficient deposition of SiC (75,76). Amorphous SiC and SiC_xN_y films have been deposited by pulsed laser deposition on single crystal silicon substrates by KrF (248 nm) excimer laser ablation of a SiC sintered target in a vacuum system at room temperature using nonreactive, Ar, and reactive, N_2, background gases at different pressure (77). The particulate density obtained in the present case (fs-PLD) was much lower than those generated by nanosecond-pulsed excimer laser ablation of SiC (78). Where it was concluded that films deposited by the femtosecond pulsed lasers were superior to those deposited by the nanosecond pulsed lasers. With long pulses such as nanoseconds, explosive ejection of liquid droplets from the target occurs because of superheating of the subsurface layers, solid-liquid phase change, thermal expansion of the material, and surface degradation. In fs-PLD, the pulses greatly modify the thermal processes in ablation because of three reasons: the coupling of a large optical field with the solid target, electron thermalization and electron-phonon coupling.

SiC, Si and alkali free glass can act as a good masking agent where the appropriate are which need to be deposited are positioned as shown in figure 3. Formation of silicon carbide ridge, line and block, basically depends on the size and shape of the mask. In addition, there are also reports on selective are laser deposition by moving the laser beam to deposit solid material from precursor gas (79). In this study, tertamrthylene silane ($Si(CH_3)_4$) as a precursor to deposit silicon carbide. These deposition rates are much higher than those that could be obtained with the 248 nm KF excimer laser depositions (with a laser fluence of 2.5 J/cm^2 at room temperature) (80) and are comparable to those obtained by the CVD method. Laser sintering is accompanied by a reaction between sintering powders or sintering powder(s) and a gas precursor. The sintering/reaction combination results in a solid layer of material compositionally different from the powder source(s). Successive layers of powder are spread and selectively laser reaction sintered to build up the desired shape (81). Selective Area Laser Deposition (SALD) Joining was utilized in fabricating joined silicon carbide structures. Specifically, silicon carbide tubes were ‘welded’ together by depositing silicon carbide from a gas phase reaction. A single laser beam deposition setup and a dual laser beam design were investigated. A gas environment of tetramethyl silane and hydrogen served as the deposition precursors (82). Selective area laser deposition vapour infiltration (SALDVI) techniques are also developed to selectively deposit SiC (83)

Nanostructured silicon carbide (SiC) has shown to exhibit superior properties (greater elasticity and strength) as compared to that of bulk SiC and has potential applications in light-emitting diodes and UV photo-detectors due to higher light-emission efficiency (84,85). There is significant interest in the synthesis of nanostructure SiC including nano-spheres, nanowires, nanorods and so on as novel functional materials for nano-scale engineering. Recently reported the chemical vapour deposition (CVD) synthesis of SiC nano-cones on the surface of silicon oxy carbide and synthesized SiC nanorods via catalyst-assisted crystallization of amorphous silicon carbon nitride. Ho et al.(84) used a vapor–liquid–solid (VLS) process to grow nano-flower-like structures with the help of gallium nitride powder. Dai et al.(85) reported the synthesis of SiC nanowires by using a carbon template method. However, these products were available just based on complicate fabrication process, cost of expensive carbon nano-tubes or the use of the explosive precursor and so on. In addition, the synthesized materials were low yield and time consuming. PLD was also deployed to synthesize random oriented SiC nanostructures without using any catalyst. However, positioning of SiC nanostructures is highly in demand. A catalyst based nanostructure growth using PLD for ZnO has been reported (86-90).

C. SiC Bulk Micromachining

The bulk micro-machining is a conventional technique, in which the selective removal of the substrate material in order to realize the miniaturized components. Bulk micromachining using chemical means are widely used in MEMS industry. The chemical etching basically involves the immersion of a substrate into a solution of reactive chemicals that will etch exposed region at the measurable rates. This chemical based etching technique can be used for bulk micro machining of single-crystal, poly and amorphous SiC (91). In the case of single-crystal generally epi-SiC on Si is used, although a BMM SiC pressure sensors using SiC on bulk substrate has been reported(92). Electrochemical etching from the backside has been used to realize 25 mm-thick membranes containing piezo-resistors (93-94). However, current micro-fabrication methods for SiC are quite limited when compared against Si. Because anisotropic wet etchants do not work well, patterning techniques based on photolithography reactive ion etching (RIE) is used for SiC. RIE etching with SF_6/O_2 plasma, SF_6/O_2 inductively coupled plasma (ICP) and deep reactive ion etching (DRIE) processes were traditional methods to etch SiC thin films, however, at very slow rates.

Photo- and electro-chemical wet etching processes are alternatives to RIE and DRIE process. In these alternatives, SiC is first anodized forming a deep porous layer and subsequently removed through thermal oxidation followed by dipping in HF. These processes suffer from poor selectivity to polysilicon and silicon dioxide sacrificial layers, low etch rates and complex steps (95,96). Another approach to patterning SiC microstructures involves the use of micro-molding, whereby an inverse pattern is etched into a sacrificial layer such as silicon dioxide. SiC is deposited into the conformal mold and then planarized using true post-processing, chemical-mechanical polishing. Another major challenge is the selective etching of SiC films or bulk materials as SiC is not etched significantly by most of acids and bases at temperature less than 600°C. This makes wet etching of SiC more difficult to accomplish and directly affects the crystallographic planes of the substrates. However Laser based micro machining can be an alternative approach (97). Due to higher chemical stability of photo chemical etching, inductively coupled with plasma and electron are used. Cyclotron resonance methods are used to etch 4H-SiC, but at very low rate (a maximum etch rate of 0.97 %m/min (for inductively coupled reactor using SF_6 based gaseous mixture).

D. Laser based Micromachining of SiC

Interaction of material with laser pulses generally involves the following fundamental processes that take place on different time scales after a pulse incidence(98). Firstly, light absorption takes place at a femtosecond timescale accompanied by ejection of excited electrons. Secondly, the excited electrons transfer their energy to the lattice in several tens of picoseconds through electron-phonon collision and induce melted zone in the bulk material. Following this, melted material evaporates on a nanosecond time scale and expands into the air in the form of atomic-sized particles in the ablation plume. Melt expulsion may also occur, termed hydrodynamic ablation, due to the recoil pressure of plume and result in large particles or clusters following the plume. The specific ablation mechanism in laser micromachining and the resulting morphology of the ablated region such as aspect ratio and sidewall roughness varies with material property, laser wavelength, power intensity as well as pulse duration. The process of multiphoton excitation of electrons and collisional ionization is reported to play vital roles in semiconductor and dielectric laser ablation with a sharp threshold of power intensity observed. This mechanism become dominant when ultra-short laser pulses are employed for ablation, whereby a much increased portion of laser energy is transferred to electrons compared to the portion further transferred to the lattice (99). Under high intensity picoseconds-pulsed laser fluence, the laser irradiated portion of n-type SiC material can be directly transformed into plasma on a few picoseconds time scale trough Coulomb explosion resulting in clean surfaces of the cleaves that outperform the results obtained with thermal ablation (100). The maximum amount of laser beam power to be converted into processing power, with no or little peripheral heating in order to keep the Heat Affected Zone (HAZ) as small as possible. The ability to focus the beam to a very small spot leads to an increase in effective process power. Laser based bulk micro aching for MEMS application has basically classified in to two based on the operation 1) Mask less bulk micro machining 2)laser assisted precise micro-machining through mask.

a. Maskless micromachining

Figure 4 shows the schematic layout of laser based maskless micro-machining. Conventional CO_2 pulsed laser has been used to produce micro holes of diameter ranging from 100 – 200 μ m and depth upto 400 ν m (100). Silicon carbide sample surface were textured using micro holes having centre to centre distance of about 200 μ m hole dimension in the range of 80 – 100 μm was machined. Square diaphragms with a nominal size of 1.5 mm × 1.5 mm were fabricated from bulk 6H–SiC wafers using a Q-switched Nd:YAG laser operating at a wavelength of 1064 nm, an average power of 0.35W, a pulse repetition rate of 3 kHz, and a pulse width of 100 ns(101). These parameters were chosen, based on previous experiments, to minimize surface roughness. Analysis of laser-machined diaphragms revealed that the average thickness of a diaphragm was 151 μ m which is composed of two layers. One is a soft, black layer with a thickness of about 83 μ m consisting of silicon, oxygen, and carbon. The other layer was a hard, virgin SiC layer with a thickness of 68 μ m (102). Nd:YAG laser at three different harmonics with pulse durations in the ps to ns regime of SiC with 1(omega) , 2(omega) , 3(omega) -Nd:YAG laser radiation is performed in various processing gas atmospheres as a function of processing variables showing the influence of the heat and pressure load onto the precision of geometric structures generated (103). The physical and chemical processes involved in micromachining with laser radiation are characterized by a machine vision system and the produced structures are analyzed by profilometry, optical and electron microscopy as well as X- photoelectron spectroscopy (104). Laser ablation of silicon carbide with 193 and 248 nm excimer nano seoncd laser and with 500 fs , 248 nm Femto second laser, it was observed that, experiments in UV shows a significant difference in the quality between 193 nm and 248 nm radiation. The cavity indicates a higher thermal impact in the case of 248 nm radiation. The application of 500 fs pulse at this particular wavelength results in an improved edge definition and surface quality of the ablated area(105).

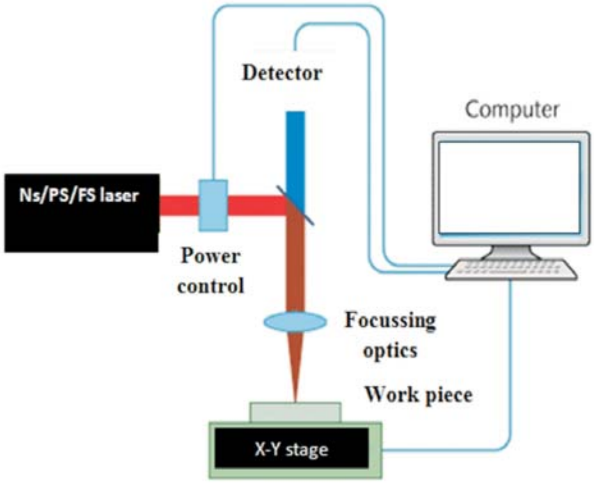

Fig. 4. Schematic layout of laser based maskless micro-machining.

b. Bulk micro machining through Mask

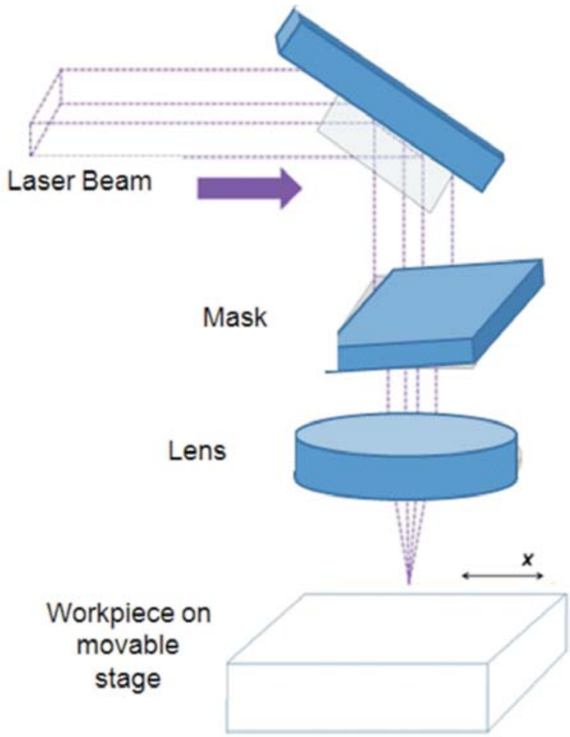

Fig. 5. Schematic layout of laser based micro-machining using mask.

Figure 5 shows the schematic layout of laser based micro-machining using mask. The mask can be replaced by a diamond tool and an IR diode laser is made to pass through a diamond tool for generating micro-scratches on 4H-SiC surface(106) . Greyscale masks have been successfully implemented in an excimer laser micromachining system to produce structures with a continuous profile (107). During this work, it was found possible to machine structures to depths of several tens of microns with no observable mask degradation. The greyscale mask transmissions were defined using a matrix of pixels whose dimension was smaller than the resolution limit of the optical system in the laser micromachining systemv(108). By reduction-projecting the greyscale mask pattern onto the workpiece, the local fluence at the workpiece could be predetermined and hence the local machining rates controlled. This enabled three-dimensional (3D) structures to be fabricated at the workpiece in a single machining operation(109). Under the experimental conditions used in this investigation, the rate at which material was ablated was found to depend linearly on the percentage transmisson of the mask(110).

E. SiC Surface Micromachining

Surface micromachining is a popular technology used for fabrication of MEMS devices (111-113). There are very large numbers of variations of how surface micro machining is performed depending on the material and etchant combinations that are used. However, the common theme involves a sequence of steps starting with the deposition of some thin film materials to act as a temporary mechanical layer onto which the actual device layers are built, followed by the deposition and patterning of thin film device layer of materials which is referred to as the structural layer; then followed by the removal of the temporary layer, thereby allowing the structural layer to move. Figure 6 merely explains the concept of surface micro machining where, the oxide layer is temporary and is commonly referred to as sacrificial layer, subsequently; a thin film layer of SiC is deposited. Finally the sacrificial layer is removed and the silicon carbide layer is free to move as a cantilever.

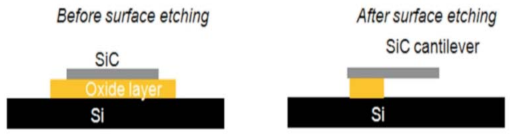

Fig. 6. Laser based micromachining with mask

As explained in the previous section, single-crystal SiC films must be grown directly on single-crystal silicon. Some of the reasons surface micromachining is so popular is that it provides for precise dimensional control in the vertical direction. This is due to the fact that the structural and a sacrificial layer thickness are defined by deposited film thickness whihc can be accurately controlled. Also, surface micro-maching provides for precise dimensional control in the horizontal direction, since the structural layer tolerance is defined by the fidelity of the photolithography and etches processes are used. Other benefits of surface micro machining are that a large variety of structure, sacrificial and etchant combinations can be used; which are compatible for MEMS device.

Fluorine-based gas mixtures have been shown to be the most effective gas for SiC etching in terms of high etch rate (114). The F species in the plasma can

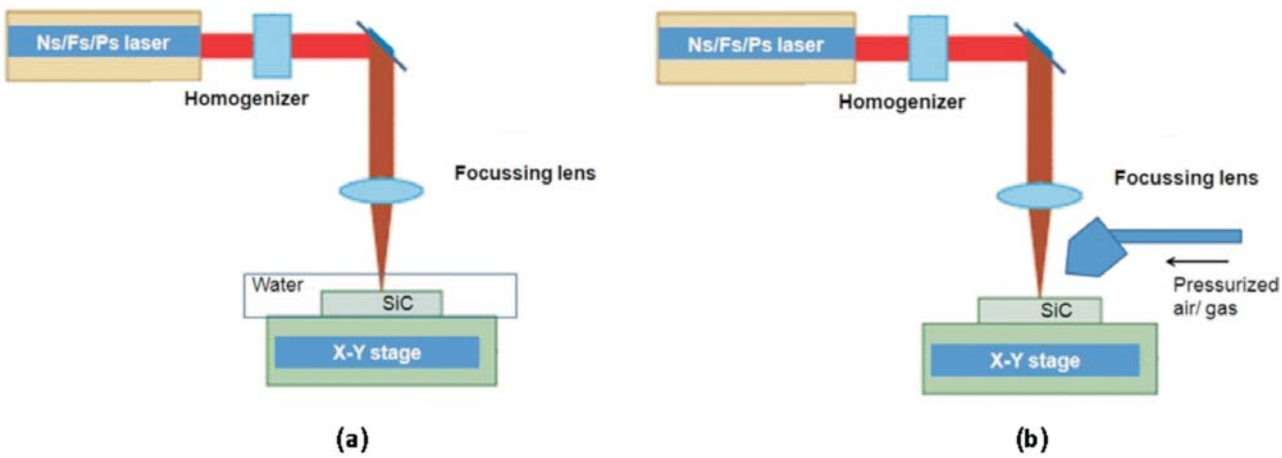

Fig. 7. Laser based surface micro etching in presence of (a) water (b) gaseous layer

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 (115-117) and there by increases etch rates. SiC etch rate of 1.05 ìm/min(118-119) 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. It was investigated (120-126) that this technique will induces little surface and the etch rates are much lower. laser based surface micromachining can act as an alternative approach, since the focussing point can be easily adjusted within the sacrificial layer, the etching can be performed in the presence of gas and water environment to remove the debris without any defect in the surface. Another mechanism, which is non thermal and referred to as photo-ablation, occurs when organic materials are exposed to ultraviolet radiation generated from excimer, harmonics YAG or other UV source.

F. Laser Based Surface Micromachining of SiC

In contrast to the chemical-based micro-fabrication methods, water assisted laser ablation of SiC is capable of higher etching rates (126-129) and precise control of via size with advancement of reducing in the number of processing steps as masking, machining independent of crystal structure, and curved surfaces. Laser etching in water, with regard to laser pulse parameters, is similar to the Laser Shock Processing process as shown in figure 7(a), with the exception that shock is not desired, while ablation is desired. This is achieved by lowering somewhat the fluence and increasing the pulse number. The fluence is taken at the level where the material at least melts, but usually vaporizes and ionizes (plasma forms).

Recently, there have been increasing studies on liquid-assisted laser micromachining, in particular on the processing parameters. It was found that liquid-assisted laser micromachining can reduce the extent of HAZ, micro-cracks, spatter re-deposition and tapering of drilling (130-132). The etching rate on liquid-assisted laser drilling strongly depends on liquid film thickness(133-135). The reduction of the extent of HAZ, micro-cracks, and spatter redeposition can explain by the cooling effect liquid. In addition, using pure water, the background etching of non-illuminated areas was eliminated. The main reason for water-assisted laser etching is the elimination of debris re-deposition in the machined area. This results in cleaner and more precise surface profiles and avoids any need for work piece after cleaning, which is usually done in an ultrasound bath(136). In some case the usage of water may result in formation of oxide layer, in those condition a thin layer of gas or air can act as in a medium in surface etching as showed in figure 7(b).

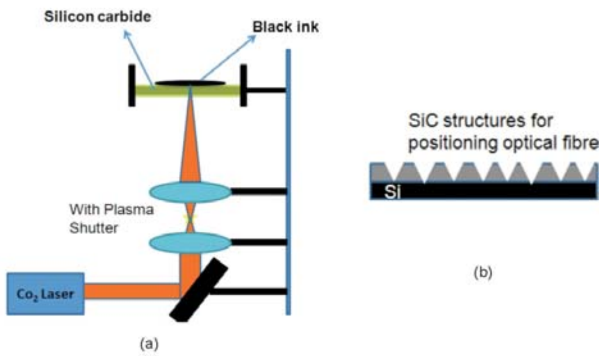

Fig. 8. (a) Schematic layout of LIBWE (b) proposed formation of V-groove on SiC

There are reports in non-thermal, laser assisted photo-electrochemical etching technique for n-type β-SiC etch rates as high as 100 μ m/min. UV radiation is necessary for efficient photo-generation of holes near the surface. These holes are transported in the presence of an external bias to the semiconductor/liquid interface, where dissolution occurs through the aniodic oxidation of the SiC and the removal of oxide present in the electrolyte (137).

Laser Induced Back side wet etching is a non thermal micro-etching in which the etchant plays a major role on surface etching, however interaction of laser have their own effect in etching. figure 8(a) shows the working principle of LIBWE in which a liquid layer is kept in contact with the silicon carbide and the silicon carbide act as a transparent medium when the Co_2 laser is made to pass thorough the surface, the laser focused on the absorbed liquid medium resulting in formation of laser induced plasmas. Confining these plasma may lead to etch silicon from the rear side. Figure 8(b) shows the proposed V-groove structure for MEMS application. Figure 9 shows the SEM micrograph of the silicon wafer, where a through hole is micro machined using deionised water as an etchant.

Detail study of this LIBWE process will lead to precise micro etching of high quality SiC surface.

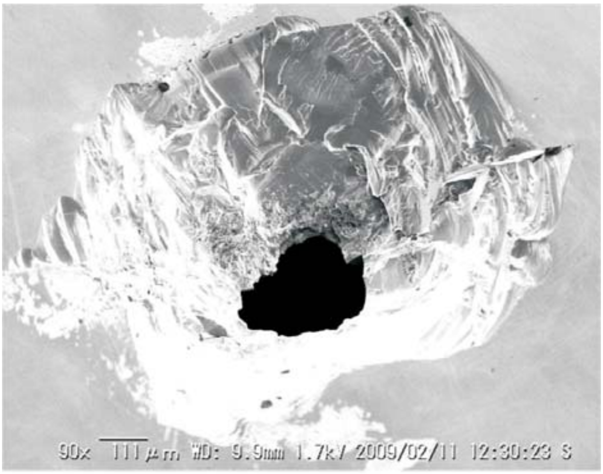

Fig. 9. Through hole developed on Si through LIBWE

IV. SUMMARY

The materials properties and the state of SiC technology was reviewed with respect to MEMS device and systems. The materials property offers existing possibilities to extend the applicability of sensor principle. The excellent stability of SiC enables operation in harsh environment such as high temperature, high pressure and chemical corrosive media. The method of micro-fabrication of SiC basically governs the reliability and effectiveness of SiC for MEMS.

Wide varieties of approaches are available for micro-fabrication and micro-etching of SiC. The conventional deposition of SiC includes CVD, PECVD etc. However the conventional systems have their own limitations towards micro-fabrication. These limitations can be overcome by laser based micro-fabrication. The conventional PLD technique can be appropriately tailored for different MEMS application, which includes 1) large area thin film 2) selective deposition 3) nanostructure development.

In addition to micro-deposition, micro-etching plays a major role for fabricating MEMS device. The conventional chemical based etching leads to defect in crystal structure. In contrast to the chemical-based micro-fabrication methods, water assisted laser ablation of SiC is capable of higher etching rates and precise control of via size with advancement of reducing in the number of processing steps as masking, machining independent of crystal structure.

The development of efficient laser based micro-fabrication and micro-etching technique will lead to efficient engineering of SiC for a remarkable development of MEMS device.

REFERENCES

[1] Lee H.Y. , Kim D.W., Sung Y.J., YeomG.Y. 2005, Fabrication of SiC micro-lens by plasma etching. *Thin Solid Films*., 475,318– 322.

[2] Park E.H., Kim M.J., Cha J.H., Kwon Y.S. 2001 Novel High-Radiance Surface-Emitting Light Emitting Diode Structure with Circular 45$ Corner Reflector and Microlens. *Jpn. J. Appl. Phys*,40, 2741.

[3] Heremans. P., Geone J., Kuijk M., Vounchx R., G.Borghs. 1997, Mushroom microlenses: optimized microlenses by reflow of multiple layers of photoresist. *IEEE Photonics Technol. Lett*, 9, 1367.

[4] Sarro. P.M. 2000, Silicon carbide as a new MEMS technology, *Sens. Actuators A*, 82,210.

[5] Mehregany. M., Zorman C.A., Roy S., Fleischman A.J., Wu C.H., Rajan N. Silicon carbide for micro - electromechanical system, *Int. Mater. Rev*., 45, 85.

[6] Yang Y.T., Ekinci K.L., Huang X.M.H., 2001, Schiavone L.M., Roukes M.L. . Monocrystalline silicon carbide nanoelectromechanical systems, *Appl. Phys. Lett*., 78,162.

[7] Roukes M.L. 2000, Nanoelectromechanical systems, *Proceedings of the Solid-State Sensor & Actuator Workshop*, Hilton Head SC, 367.

[8] Yasseen A., Wu H., Zorman C.A., Mehregany M., 1999, Fabrication and testing of surface micromachined silicon carbide micromotors, *Proc. IEEE-MEMS 99, Orlando, FL, USA*, 17–21 Jan. pp. 644–649

[9] Sarro P.M., French P.J., Gennissen P.J.T., 1996, New developments in the integration of micromachined sensors, (invited paper) Proc. SPIE Micromachining and Microfabrication '96 Symposium, Austin, TX, USA, 14–15 October, *SPIE Vol. 2882*, pp. 26–36.

[10] Tong. Q.-Y., Gösele U., 1999. Semiconductor Wafer Bonding: Science and Technology, *Wiley, USA,*

[11] Berthold. A., Sarro P.M., Vellekoop M.J., Nicola L. 1999. A novel technological process for glass-to-glass anodic bonding, *Proc. Transducers 99*, Sendai, Japan, June 7–10, pp. 1324–1327.

[12] Belouet C.1996, Thin film growth by the pulsed laser assisted deposition technique, *App. Surf. Sci*., 96-98, 630-642.

[13] Willmott P.R., 2000, Huber J.R. Pulsed laser vaporization and deposition, *Rev. Modern Phys.*, 72, 315-328.

[14] Saenger K. L. 1993, Pulsed laser deposition part I a review of process characteristics and capabilities, *Proc. Adv. Mat,*.2, 1-24.

[15] Chrisey. D.B., HublerG. K. 1994, Pulsed laser deposition of thin films, Wiley, New York, 1,.

[16] Womack M., Vendan M., Molian P. 2000, Femtosecond pulsed laser ablation and Deposition of thin films of polytetrafluoroethylene, *App. Surf. Sci.,*221, 99-109.

[17 Maine P., Strickland D., Bado P., Pessot M.,1998 Mourou G. Generation of ultrahigh peak power pulses by chirped pulse amplification, *IEEE Journal of Quantum Electronics,* 24, 398.

[18] Bloembergen. N. 1974, Laser-induced electric breakdown in solids, *IEEE Journal of Quantum Electron,*10, 375.

[19] Nolte S., Momma C., Jacobs H., 1997, Tunnermann A., Chichkov B.N., Welling H.. Ablation of metals by ultrashort laser pulses, *J. Opt. Soc. Amer. B.*, 14,2722.

[20] Liu X., Du D., Mourou.G. 1997, Laser ablation and micromachining with ultrashort laser pulses, *IEEE J. Quantum Electron*, 33,1706.

[21] John Wiley and Sons, 1989, “Accidental discoveries in science,” New York;.

[22] http://www.ioffe.rssi.ru/SVA/NSM/Semicond/SiC/ebasic.html 2005 "Electrical properties of SiC,".

[23] Altus E., Konstantino E., 2001, Optimum laser surface treatment of fatigue damaged Ti–6Al–4V alloy, Materials Science and Engineering A, 302, 1, 100-105.

[24] Kisina Yu. B. *et al*, 1995, laser surface alloying of selenium Metal science and heat treatment, 37, 1-2.

[25] Kac S. *et al*, 2007, “Structure and properties of the bronze laser alloyed with titanium”, Applied Surface Science, 253, 7895–7898.

[26] Jianhua Yao, Liang Wang *et al,* 2007, “Surface Laser alloying of 17-4PH SS steam turbine blades”, Optics and Laser technology, 1-6.

[27] Hatanaka Y., 2001, “Excimer laser doping technique for II-VI semiconductors”, Applied surface science, 175-176 , 462-467.

[28] Technical report on “Laser surface cladding a literature survey”, Leula Tekniska univ, 2000.

[29] Wange D.G. *et al*, 2008 “In situ synthesis of hydroxyapatite coating by laser cladding” Colloids and Surfaces B: Biointerfaces.

[30] Karl-Hermann Richter *et al*, 2004, “laser cladding of the titanium alloy Ti6242 to restore damaged blades”, Proce of the 23rd Int Congress on Applications of Lasers and Electro-Optics

[31] Sandipm Halder *et al*, 2006, “Laser annealing of BST thin films with reduce cracking atb an elevated temperatures” , Material science and Engineering B.

[32] Choyke W.J , Matsunami H., Pensl G., 1997, “*Silicon Carbide–A review of fundamental questions and applications to current device technology,”*).

[33] tp://www.ifm.liu.se/matphys/new_page/research/sic/index.html 2005 "Silicon Carbide," (Dec).

[34] Brown D.M, Downey E., Kretchmer J., Michon G., Shu E., Schneider.D. SiC flame sensors for gas turbine control systems, *Solid-State Electron.*,1998, 42, 755.

[35] Weitzel C.E., Moore K. E., 1998, “Silicon carbide and gallium nitride RF power devices,” In: S. J.Pearton, R.J. Shul, E. Wolfgang, F.Ren, S. Tenconi (eds.) “Power Semiconductor Materials and Devices,*” Materials Research Society*, Warrendale, PA, 483, 111-120.

[36] Fazi C., Neudeck P. 1998, Use of wide-bandgap semiconductors to improve intermodulation distortion in electronic systems, In: G. Pensl, H. Morkoc, B.

[37] Monemar, E. Janzen (eds.) “Silicon Carbide, III-Nitrides, and Related Materials,*”Materials Science Forum, 264-268.*

[38] Nagai T., Itoh M., 1990, “SiC thin-film thermistors,” *IEEE Trans. Ind. Applicat.,*26, 1139.

[39] Arbab A., Spetz A., Lundstrom.I. 1993, Gas sensors for high temperature operation based on metal oxide silicon carbide (MOSiC) devices, *Sensors and Actuators B,*15–16, 19–23.

[40] Hoshino K., Shimoyama.I. 2000, Design and performance of a micro-sized biomorphic compound eye with a scanning retina, *J. Microelectromech. Syst*, 9, 32.

[41] Saha H., Roy Chaudhuri.C. 2009, Complementary Metal Oxide Semiconductors Microelectromechanical Systems Integration, *Advances in Microelectromechanical Systems*, 2009,59(6),63.

[42] De Busschere, B.D. & Kovacs, G.T.A. 2001, Portable cell based biosensor system using integrated CMOS cell cartridges, *Biosensors & Bioelectronics*, 16, 543-56.

[43] Dec, A. & Suyama, K. 1998, Micromachined, electromechanically tunable capacitors and their applications, to RF ICS, *IEEE Trans. Microwave Theory Tech.*, 46, 2587-595.

[44] Kim, M.; Hacker, J.B.; Mihailovich, R.E. & DeNatale, J.F. 2001, A. DC-to-40GHz four-bit RF MEMS true-time delay network, *IEEE Microwave Wireless Comp. Lett.*, 11, 56-58.

[45] Gwiy-Sang Chung, Roya Maboudian. 2005, Bonding characteristics of 3C-SiC wafers with hydrofluoric acid for high-temperature MEMS applications, Sensors and Actuators A: Physical, 119(2),599.

[46] Krotz G., Wondrak W., Eickhoff M., Lauer V., Obermeier E., Cavalloni C., 1998 New high-temperature sensors for innovative engine management, *Springer Proceedings on Advanced Microsystems for Automotive Applications*, Berlin, p. 223.

[47] Casady B., 1996, Johnson.R.W. Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: a review, *Solid-State Electron.*, 39, 1409.

[48] Mehregany M., Zorman C.A. 1999, SiC MEMS: opportunities and challenges for application in harsh environments, *Thin Solid Films*, 355/356,518.

[49] Yang, Y.T., Ekinci, K.L., Huang, X.M.H., Schiavone, L.M., Roukes, M.L., Zorman, C.A. and Mehregany, M. 2001, 'Monocrystalline silicon carbide nanoelectromechanical systems', *Applied Physics Letters*, 78, 162.

[50] Nguyen, C.T-C. 1997, 'High-Q micromechanical oscillators and filters for communications', *Proceedings of I997 IEEE International Symposium on Circuits and System*, Hong Kong, 2825.

[51] Roy, S., DeAnna, R.G., Zorman, C.A. and Mehregany, M. 2002, Fabrication and characterization of polycrystalline SiC resonators', *IEEE Transactions on Electron Devices*, 49, 2323.

[52] Jiang, L., Cheung, R., Brown, R. and Mount, A. 2003, Inductively coupled plasma etching of SiC in SF6/O2 and etch-induced surface chemical bonding modifications, *Journal of Applied Physics*, 93,1376.

[53] Pakula, L.S., Yang, H. and French, P.J. 2003 A CMOS compatible SiC accelerometer, *Proceedings of IEEE Sensors, 2, 761.*

[54] Pakula, L.S., Yang, H., Pham, H.T.M., French, P.J. and Sarro, P.M. Fabrication of a CMOS compatible pressure sensor for harsh environment, *Proceedings of 16th IEEE International MEMS Conference*, 19–23 January, Kyoto, Japan, 502.

[55] Zappe, S., Franklin, J., Obermeier, E., Eickhoff, M., Moller, H., Krotz, G., Rougeot, C., Lefort, O. and Stoemenos, J.2001, 'High temperature 10 bar pressure sensor based on 3C-SiC/SOI for turbine control applications', *Materials Science Forum*, 353, 753.

[56] Ziermann, R., von Berg, J., Obermeier, E., Wischmeyer, F., Niemann, E., Möller, H., Eickhoff, M. and Krötz, G. 1999, High temperature piezoresistive SiC-on-SOI pressure sensor with on chip SiC thermistor', *Materials Science and Engineering B*, 61–62, 576.

[57] Atwell, A.R., Okojie, R.S., Kornegay, K.T., Roberson, S.L. and Beliveau, A. 2003,'Simulation, fabrication and testing of bulk micromachined 6H-SiC high-*g* piezoresistive accelerometers', *Sensors and Actuators A*,104, 11.

[58] Okojie, R.S., Atwell, A.R., Kornegay, K.T., Roberson, S.L. and Beliveau, 2001, A. Design considerations for bulk micromachining 6H–SiC high-G piezoresistive accelerometers, *Technical Digest 15th International Conference on MEMS*, p.618.

[59] Okojie, R.S., Ned, A.A. and Kurtz, A.D. 1998, 'Operation of 6H-SiC pressure sensor at 500$C', *Sensors and Actuators A*, 66, 200.

[60] Baranzahi, A., Tobias, P., Spetz, A.L., Lundström, I., Mårtensson, P., Glavmo, M., Göras, A., Nytomt, J., Salomonsson, P. and Larsson, H. 1997 'Combustion and emission formation in SI engines', *SAE Technical Paper Series 972940*, p.231.

[61] Solzbacher, F., Imawan, C., Steffes, H., Obermeier, E. and Eickhoff, M. 2001,'A highly stable SiC based microhotplate NO2 gas-sensor, *Sensors and Actuators B*, 78,216.

[62] Strokan, N.B., Ivanov, A.M., Savkina, N.S., Strelchuk, A.M., Lebedev, A.A., Syvajarvi, M. And Yakimova, R.2003, Detection of strongly and weakly ionizing radiation by triode structure based on SiC films, *Journal of Applied Physics*, 93,5714.

[63] Wise, K.D. 1998, Special issue on integrated sensors, microactuators and Microsystems (MEMS), *Proceedings of the IEEE*, 86, 1531.

[64] Wu, C.H., Zorman, C.A. and Mehregany, M. 2006, Fabrication and testing of bulk micromachined silicon carbide piezoresistive pressure sensors for high temperature applications, *IEEE Sensors Journal*, 6,316.

[65] Xie, K., Femish, J.R., Zhao, J.H., Buchwald, W.R. and Cacas, 1995, L.Low damage and residue-free dry etching of 6H–SiC using electron cyclotron resonance plasma, *Applied Physics Letters*, 67, 368.

[66] Zorman, C.A., Fleischman, A.J., Dewa, A.S., Mehregany, M., Jacob, C., Nishino, S. and Pirouz, P. 1995, 'Epitaxial growth of 3C–SiC films on 4 in diam (100) silicon wafers by atmospheric pressure chemical vapor deposition', *Journal of Applied Physics*, 78, 5136.

[67] Zorman, C.A., Fu, X.A. and Mehregany, M. 2006, Deposition techniques for SiC MEMS',*Silicon Carbide*

MEMS for Harsh Environments, London: Imperial College Press.

[68] Nishino, S., Powell, J.A. and Will, H.A. 1983,'Production of large-area single-crystal wafers of cubic SiC for semiconductor devices, *Applied Physics Letters*, 42,460.

[69] Powell, J.A., Matus, L.G. and Kuczmarski, M.A. 1987, 'Growth and characterisation of cubic SiC single-crystal films on Si', *Journal of Electrochemical Society*, 134,1558.

[70] Bischoff, L., Teichert, J. and Heera, V. 2001, 'Focused ion beam sputtering investigations on SiC', *Applied Surface Science*, 184, 372.

[71] Boo, J.H., Lee, S.B., Yu, K.S., Sung, M.M. and Kim, Y. 2000, 'High vacuum chemical vapour deposition of cubic SiC thin films on Si (001) substrates using single source precursor', *Surface Coatings Technology*, 131, 147.

[72] Chen, J., Scofield, J. and Steckl, A.J. 2000, Formation of SiC SOI structures by direct growth on insulating layers', *Journal of Electrochemical Society*, 147, 3845.

[73] Flannery, A.F., Mourlas, N.J., Storment, C.W., Tsai, S., Tan, S.H., Heck, J., Monk, D., Kim, T., Gogoi, B. and Kovacs, G.T.A. 1998, 'PECVD silicon carbide as a chemically resistant material for micromachined transducers', *Sensors and Actuators A*, 70, 48.

[74] Sarro, P., deBoer, C.R., Korkmaz, E. and Laros,1998 J.M.W. Low-stress PECVD SiC thin films for IC-compatible microstructures, *Sensors and Actuator A*, 67, 175.

[75] Klumpp, A., Schaber, U., Offereins, H.L., Kuhl, K. and Sandmaier, H. 1994, Amorphous SiC and its application in silicon micromachining'*Sensors and Actuators A*, 41–42, 310.

[76] Womack M., Vendan M., Molian P., 2004, "Femtosecond pulsed laser ablation and deposition of thin films of polytetrafluoroethylene," *App. Surf. Sci.,* 221, 99-109.

[77] Reitano R., Baeri P., Marino N. 1996, Excimer laser induced thermal evaporation and ablation of silicon carbide, *App. Surf. Sci.*, 96-98, 302-308.

[78] Kim C-S., Song S.C., Yeol Lee S. 2000, Fabrication of novel 22 GHz hairpin type HTS microstrip filter using laser ablated thin films, *Appl. Surf. Sci.,* 168, 316.

[79] Chrisey D.B., Hubler G.K., 1994 "Pulsed laser deposition of thin films," , 55-81.

[80] Han X., Wang G., Jie J., Zhu X., Hou J.G., 2005, "Properties of Zn1-xCoxO thin films grown on silicon substrates prepared by pulsed laser deposition," *Thin Solid Films,* 491, 249.

[81] Maine P., Strickland D., Bado P., Pessot M., Mourou G., 1988, Generation of ultra high peak power pulses by chirped pulse amplification, *IEEE Journal of QuantumElectronics,* 24, 398.

[82] Bloembergen. N. 1974, Laser-induced electric breakdown in solids, *IEEE Journal of Quantum Electron,* 10, 375–386.

[83] Nolte S., Momma C., Jacobs H., Tunnermann A., Chichkov B.N., Welling.H. 1997, Ablation of metals by ultrashort laser pulses, *J. Opt. Soc. Amer. B.*, 14, 2716.

[84] Rimai L., Ager R., Hangas J., Logothetis E. M., Nayef AbuAgeel 1993, Pulsed laser deposition of SiC films on fused silica and sapphire substrates, *J. Appl. Phys*, 73, 8242.

[85] Tenth R.I., Balooch M., Connor A. L., Bernardez L. , Olson B., Allen M. J., Siekhaus W. J., and Olander D. R., 1990, in Laser Ablation for Materials Synthesis, edited by Paine D. C. and Bravman J. C., *Mater. Res. Sot. Symp. Proc.* Vol. 191 (Materials Research Society, Pittsburgh, PA, p. 61.

[86] Zong, G., J.V. Tompkins, W.R.Thissell, Sajot, and Marcus, 1991 "Processing Problems Associated With Gas Phase Solid Freeform Fabrication Using Pyrolytic Selective Area Laser Deposition", *Proceedings of the Sol" Freeform Fabrication Symposium, edited by Harris L. Marcus, Joeseph J.Beaman,David L. Bourell, and Richard H. Crawford, The University of Texas at Austin, Austin,Texas, August 12-14, 1991, p.271.*

[87] Radziemski, Leon, and David A. Cremers, 1989 Laser Induced Plasmas and Applications, Marcel Drekker Inc., New York, NY, pp 327-9.

[88] Palani .I.A., Nakamura D., Okazaki K., Highasiata M. , Okada T. 2012, Structural and optical properties of Sb: Al co-doped ZnO nanowires synthesized using Nanoparticle Assisted Pulsed Laser Deposition (NAPLD) with Sb as catalyst *Journal of Alloys and Compounds*, *527*, *1126*

[89] Palani, I. A. D, Nakamura, K.Okazaki, K.Sakai, Higashihata, M, T.Okada 2012, "Influence of Sb in synthesize of ZnO nanowire using sandwich type substrate in carbothermal evaporation method" *Applied Surface Science, 258,8,361.*

[90] Palani. I.A., Nakamura. D, Okazaki, K., Higashihata, M, Okada T. 2011. "Influence of Sb as a catalyst in the growth of ZnO nano wires and nano sheets using Nanoparticle-Assisted Pulsed-Laser Deposition (NAPLD)" *Material Science and Engineering B* (doi:10.1016/j.mseb.09.017).

[91] Bischoff, L., Teichert, J. and Heera, V. 2001, Focused ion beam sputtering investigations on SiC, *Applied Surface Science, 184, 372.*

[92] Dong, Y., Zorman, C. and Molian, P. 2003, Femtosecond pulsed laser micromachining of single crystalline 3C– SiC structures based on a laser-induced defect-activation process, *Journal of Micromechanics and Microengineering, 13, 680.*

[93] Okojie, R.S., Ned, A.A. and Kurtz, A.D. 1998, Operation of 6H-SiC pressure sensor at 500$C,*Sensors and Actuators A, 66, 200.*

[94] Mehregany, M. and Zorman, C.A.1999, SiC MEMS: opportunities and challenges for applications in harsh environments, *Thin Solid Films*, 355, 518.

[95] Jiang, L., Plank, N.O.V., Blauw, M.A., Cheung, R. and van der Drift, E. 2004, Dry etching of SiC in inductively coupled Cl2/Ar plasma, *Journal of Physics D: Applied Physics*, 37,1809.

[96] Rajan, N., Zorman, C.A., Mehregany, M., DeAnna, R. and Harvey, R. 1998, Performance of 3C-SiC thin films as protective coatings for silicon-micro-machined atomizers, *Thin Solid Films*, 315,170.

[97] C. Fazi, P. Neudeck, 1998, "Use of wide-bandgap semiconductors to improve intermodulation distortion in electronic systems," In: G. Pensl, H. Morkoc, B. Monemar, E. Janzen (eds.) "Silicon Carbide, III-Nitrides, and Related Materials,*" Materials Science Forum,* 264-268. Trans Tech, Switzerland, 913-915.

[98] Nagai. T., Itoh M., 1990, "SiC thin-film thermistors," *IEEE Trans. Ind. Applicat.,* 26, 1139–1143.

[99] Schaffer, C. B., J. F. Garcia, and E. Mazur. 1993, Bulk heating of transparent materials using a high-repetition-rate femtosecond laser. *Applied Physics a-Materials Science & Processing*, 76(3):351-354

[100] Stuart, B. C., et al.,1996, Nanosecond-to-femtosecond laser-induced breakdown in dielectrics. *Physical Review 53(4):1749-1761.*

[110] Maine. P., Strickland D., Bado P., Pessot M., Mourou G., 1988, "Generation of ultrahigh peak power pulses by chirped pulse amplification," *IEEE Journal of Quantum Electronics,* 24, 398.

[111] Bloembergen. N., 1974, "Laser-induced electric breakdown in solids," *IEEE Journal of Quantum Electron,* 10, 375–386.

[112]Nolte. S., Momma C., Jacobs H., Tunnermann A., Chichkov B.N., Welling H., 1997, "Ablation of metals by ultrashort laser pulses," *J. Opt. Soc. Amer. B.*, 14, 2716–2722.

[113] Liu. X., Du D., Mourou G., 1997, "Laser ablation and micromachining with ultrashort laser pulses," *IEEE J. Quantum Electron*, 33, 1706–1716.

[114] Rizvi. N.H., 2002 "Femtosecond laser micromachining:Current status and applications," *Focused on Laser Precision Microfabrication,.*

[115] Ohn Wiley and Sons, 1989 "Accidental discoveries in science," New York;.

[116] Varel, H., et al. 1997, Micromachining of quartz with ultrashort laser pulses. *Applied Physics A (Materials Science Processing), 65(4-5).*

[117] Xianghua Wang, Giuseppe Yickhong Mak and Hoi Wai Choi 2012. Laser Micromachining and MicroPatterning with a Nanosecond UV Laser, *Micromachining Techniques for Fabrication of Micro and NanoStructures, Dr. Mojtaba Kahrizi (Ed.), ISBN: 978-953-307-906-6.*

[118] Kruusing A. Underwater and water-assisted laser processing. Part 1. General features, steam cleaning and shock processing. (This issue: PII: S0143-8166(02)00142-2).

[119] Dolgaev SI, Lyalin AA, Simakin AV, Shafeev GA. 1996, Etching of sapphire assisted by copper-vapor laser radiation. *Quantum Electron* 1996;26(1):65–8.

[120] Dolgaev SI, Lyalin AA, Simakin AV, Shafeev GA. 1996 Fast etching of sapphire by visible range quasi cw laser radiation. *Appl Surf Sci*;96–98:491–5.

[121] Wang J, Niino H, Yabe A. 2000 Micromachining by laser ablation of liquid: superheated liquid and phase explosion. *Proc SPIE* ;3933:347–54.

[122] Geiger M, Becker W, Rebhan T, Hutfless J, Lutz N.1996 Increase of efficiency for the XeCl excimer laser ablation of ceramics. *Appl Surf Sci,* ;96–98:301–

[123] Sakka T, Iwanaga S, Ogata YH, Matsunawa A, Takemoto T. 2000 Laser ablation at solid–liquid interfaces: an approach from optical emission spectra. *J Chem Phys,* ; 112(19):8645–53.

[124] Shafeev GA, Simakhin AV. 1992 Spatially confined laser-induced damage of Si under a liquid layer. *Appl Phys A ;54:311–6.*

[125] Dupont A, Caminat P, Bournot P. 1995 Enhancement of material ablation using 248, 308, 532, 1064 nm laser pulse with a water film on the treated surface. *J Appl Phys* ;78(3):2022–8.

[126] Ageev VA. 1975 Study of the light erosion of metals in liquids. *Zh Prikl Spektrosk*,;23(1):42–6.

[127] Brook MR, Shafeev GA. 1992, Laser-assisted engraving of HgCdTe under a liquid layer. *Appl Surf Sci 54, 336–40.*

[128] Shafeev GA, Simahkin AV. 1994 Laser-assisted etching-like damage of Si under a liquid layer. *Laser Phys ;4(3):631–4.*

[129] Simakin AV, Shafeev GA.1995 Laser-assisted etching-like damage of SiC. *Appl Surf Sci,* ;86:422–7.

[130] Grasegger JM. 1998 Rapid prototyping of microfluidic structures with Nd: YAG-laser-ablation. Reichl H, Obermeier E, editors. Micro System Technologies 98, 6th International Conference on Micro Electro, Opto, Mechanical Systems and Components, Potsdam, Berlin, Offenbach: VDE-Verlag GmbH, p. 439–44.

[131] Morita N, Ishida S, Fujimori Y, Ishikawa K. 1988 Pulsed laser processing of ceramics in water. *Appl Phys Lett ;52(23):1965–6.*

[132] Shafeev GA, Obraztsova ED, Pimenov SM.1997 Laser-assisted etching of diamonds in air and in liquid media. *Appl Phys A* ;65(1):29–32.

[133] Shafeev GA, Obraztsova ED, Pimenov SM. 1997 Laser-assisted etching of diamonds in air and in liquid media. *Mater Sci Eng B* ;46(1–3):129–32.

[134] Zhu S, Lu YF, Hong MH, Chen XY. 2001; Laser ablation of solid substrates in water and in ambient air. *J Appl Phys, 89(4):2400–3.*

[135] Ohara J, Nagakubo M, Kawahara N, Hattori T. 1997. High aspect ratio etching by infrared laser induced micro bubbles*. Proceedings of the IEEE Tenth Annual International Workshop on Micro Electro Mechanical Systems, New York: IEEE, 1997. p. 175–9.*

[136] Stanislawki M, Meister J, Mitra T, Ivanenko MM, Zanger K, Hering P. 2001 Hard tissue ablation with a free running Er:YAG and Q-switched CO2 laser: a comparative study*. Appl Phys B* ;72: 115–20.

[137] Kennedy PK, Hammer DX, Rockwell BA. 1997 Laser-induced breakdown in aqueous media. *Prog Quantum Electron ;21(3):155–248.*

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