Manufacturing and Applications of Polymer and Ceramic MEMS from a Novel Material-Process for Harsh Environments

Li-Anne Liew and Rishi Raj[1]
Department of Mechanical Engineering, University of Colorado at Boulder
Boulder, CO 80309-0427

ABSTRACT

This paper summarizes very recent developments in the MEMS application of a novel material-class, manufactured by new processing methods. This technology has two unique aspects: (1) The materials form a continuum from high temperature polymers to ultrahigh temperature ceramics. We call them polymer-derived-ceramics (PDCs). In addition to being mechanically robust and chemically inert, the PDCs can be functionalized to embody electronic, optical and magnetic properties. (2) PDC-MEMS are processed from liquid precursors by a simple UV photolithographic photo-curing process. Multilayer structures can be made by stereo lithography or by simple bonding of the polymer structures. The PDC-MEMS technology will be demonstrated by two examples: an optical grating made from the transparent polymer version of the PDC, and a microigniter operating at 1300-1500oC made from the ceramic version. A special feature of the Colorado work is the development of a real-time human-machine-interface (HMI) along-side the design and testing of the MEMS devices. For example, a live HMI for the microigniter gives information such as tip temperature, remaining life and damage accumulation. Finally, the PDC-MEMS technology is inexpensive.

Key Words: Polymer MEMS, Ceramic MEMS, High Temperature, PDC, SiCN

1. INTRODUCTION

1.1 Motivation: MEMS for High-Temperatures and Harsh Environments

Microelectromechanical Systems (MEMS) is an enabling technology with many applications ranging from telecommunications to biotechnology. However, a broad set of applications for which MEMS has not so far been successfully employed commercially are those involving ultrahigh temperatures (above 1000 ^{o}C) and/or highly corrosive environments. Examples of such applications include sensors in gas turbine engines, devices for high-power laser systems, or MEMS as micro power generation sources. One reason for the absence of MEMS in these applications lies in the lack of suitable materials.

High-Temperature/Harsh-Environment MEMS should be made from materials that possess the necessary refractory properties – such as creep resistance, oxidation resistance, thermal shock etc. – at ultrahigh temperatures and in corrosive environments. The materials commonly used in existing MEMS technology, such as silicon, and many polymers and metals, do not possess the necessary refractory properties. Figure 1 shows a polysilicon micro mirror that has suffered thermally-induced damage from high optical power density [1].

Ceramics present an attractive alternative for such applications, but at the same time, these materials must be micromachineable and preferably compatible with existing MEMS fabrication/packaging technologies so as to enable integration with the existing infrastructure. Several technologies have been developed for fabricating microsystems from various ceramics such as SiC [2], Al_2O_3 [3] and low-temperature co-fired ceramics [4]. Of these, the silicon carbide technology is probably the most mature, encompassing both semiconductor devices and MEMS for high-temperature applications. Despite the recent interest in MEMS harsh environments, many of the recently-developed ceramic MEMS technologies still possess disadvantages: the technologies based on sintered powders of micro casting of slurries pose a

[1] Rishi.Raj@Colorado.edu

Smart Structures and Materials 2003: Smart Electronics, MEMS, BioMEMS, and Nanotechnology,
Vijay K. Varadan, Laszlo B. Kish, Editors, Proceedings of SPIE Vol. 5055 (2003)
© 2003 SPIE · 0277-786X/03/$15.00

fundamental lower limit on the size due to the finite particle dimensions which can be on the same order of the devices that we wish to fabricate. MEMS made from deposited ceramic films such as SiCN and diamond, have proven to be technically difficult to fabricate due to the inherent chemical inertness of ceramics which make them difficult to etch.

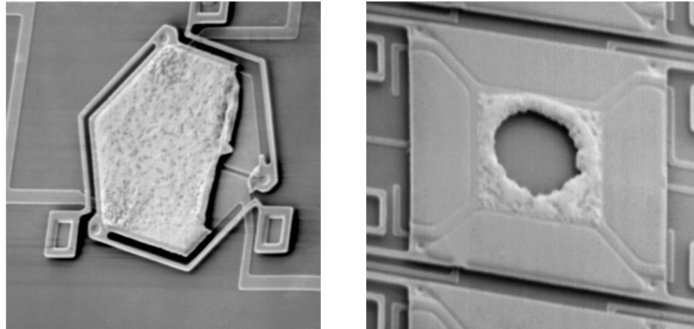

Figure 1. Polysilicon micromirror failure from 12.65 mW (left) and 9.35 mW (right) optical power for a duration of 3 seconds [1].

Enter a new class of novel materials known as polymer-derived ceramics (PDCs). These materials are at present relatively unknown outside of a handful of academic institutions, but are gaining widespread interest due to their remarkable properties and unique, low-cost processing. Figure 2 shows phase diagrams of two types of PDCs – silicon oxycarbide (SiOC) and silicon carbonitride (SiCN). Most of the research to date has focused on synthesis routes for PDCs and characterization of various properties. Our group at the University of Colorado at Boulder has, over the last few years, conducted exploratory research into the science and technology of polymer-derived SiCN with an emphasis on MEMS applications for harsh environments.

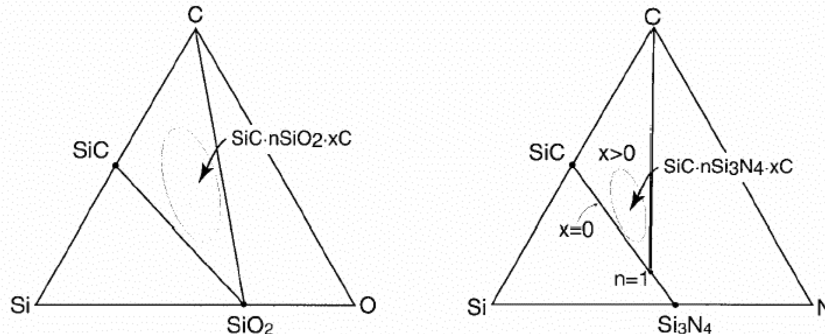

Figure 2. Phase diagrams of polymer-derived SiOC and SiCN [5].

1.2 Background on Polymer-Derived Ceramics

Polymer-derived ceramics are a recently-developed class of materials. Developed in their present form in the early 1990s [6], these materials are unique in both their properties and their processing.

Polymer-derived SiCN is unique in several ways. First, unlike other ceramic MEMS that are fabricated via thin-film deposition [2] or sintered powders [3], SiCN is derived from liquid polymers, thus the fabrication of MEMS closely resembles the fabrication of polymer MEMS and as such is lower cost than many alternative ceramic technologies. Second, the amorphous structure of the SiCN results in much higher oxidation resistance [7], creep resistance [8] and thermal shock at ultrahigh temperatures, the glass transition temperature of SiCN being 1500 ^{o}C-1800 ^{o}C which is the highest reported for any amorphous material. SiCN is thus a more ideal material for ultrahigh temperature and harsh environment applications. Table 1. lists some properties of SiCN. Third, SiCN can be readily functionalized to produce a

class of related materials possessing tailored electrical, magnetic, or optical properties for specific applications. For example, its semiconductive [9, 10] properties make this material ideal for high temperature MEMS applications.

Recently, other research groups have also developed microfabrication technologies for PDCs [11 , 12]. However, our approach differs from these contemporary works in that we have focused on realizing functional MEMS devices from SiCN [13]. Among the devices that have been demonstrated are electrostatic actuators [14, 15] and thermal actuators [16].

In this paper we summarize our recent developments PDC MEMS technology. In particular, we show the versatility of this material system by demonstrating devices made from both the polymeric and ceramic states.

	SiCN	SiC	Si_3N_4
Density (g/cm_3)	2.35	3.17	3.19
E, Modulus (GPa)	150	405	405
Poisson's ratio	0.17	0.14	0.24
CTE ($\times 10^{-6}$/K)	~3	3.8	2.5
Hardness (GPa)	25	30	28
Strength (MPa)	1100	418	700
Toughness ($MPa.m^{1/2}$)	3.5	4-6	5-8
Thermalschock FOM*	2300	270	890
Creep rate at 1350 °C (s^{-1})	$<10^{-8}$	$\sim10^{-9}$	$\sim10^{-9}$
Oxidation rate at 1350 °C($cm/hr^{1/2}$)	$\sim10^{-5}$	$\sim10^{-5}$	$\sim10^{-5}$

* - Strength/(E-modulus.CTE)

Table 1. Properties of polymer-derived SiCN.

2. FABRICATION OF PDC MEMS

2.1 Overall Fabrication Process

The overall fabrication process for polymer-derived ceramic MEMS is shown in Figure 3. We start with a liquid polymer precursor, which is a poly-urea-methyl-vinyl-silazane (commercially available as Ceraset^{TM} from Kion Corp.). Catalysts are added (A) to enable polymerization to occur either at low temperatures (<150 ^{o}C) or by UV exposure. MEMS-scale structures are then shaped from the liquid polymer (B). This polymer-micromachining process is based on semiconductor lithography techniques, and results in batch fabrication of planar polymer structures on a silicon wafer. Structures with single-layer thickness ranging from 5 to 500 microns may be easily fabricated. These polymer structures are then crosslinked at 400 ^{o}C under pressure to increase the material's density.

An important advantage of PDC MEMS fabrication is that aspect ratios ranging from film-like to high aspect ratios (over 20:1) [17] can be easily obtained via standard UV photolithography.

At this point, the structures may be retained and used in their polymer state, the poly-urea-methyl-vinyl-silazane being a organic/inorganic glass that has been shown to retain its optical and mechanical properties up to 250 ^{o}C [18].

Alternatively, the polymer may be pyrolyzed into a ceramic (C) by heating to 1000 ^oC in an inert atmosphere. This thermal decomposition results in ceramic MEMS structures that retain their original shape but undergo up to 30% linear shrinkage. The resulting material is an amorphous alloy of silicon, carbon and nitrogen (Si-C-N). This ceramic possesses many favorable refractory properties, as already mentioned.

An optional step is to follow pyrolysis with a high-temperature annealing heat treatment. Unlike most ceramics which are electrical insulators, SiCN is a semiconducting material and is insulating at room temperature. The result of this heat treatment is to lower the SiCN resistivity to where it is electrically conductive at room-temperature. The semiconducting and multifunctional nature of SiCN – in addition to its refractory properties – makes this material very attractive for MEMS applications, which often require electro-thermo-mechanical transduction. Steps B through D will now be described in more detail.

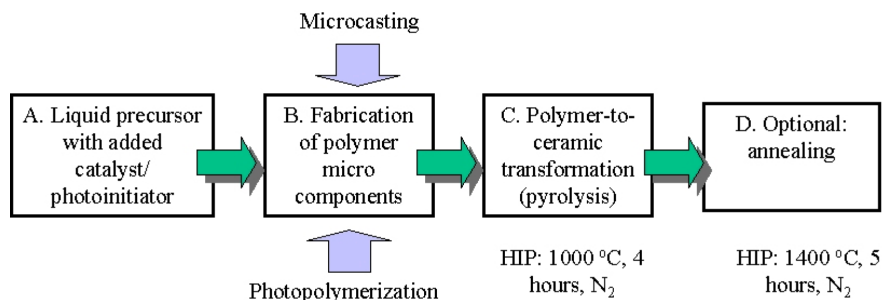

Figure 3. Overall fabrication process for PDC MEMS.

2.2 Polymer Micromachining

Polymer micromachining refers to the fabrication of solid polymer MEMS structures from the liquid precursor. It is the first step in obtaining either polymer- or ceramic MEMS components of the desired geometry. A significant challenge in micromachining polysilazanes lies in the material's high sensitivity to moisture, its reactivity with many common cleanroom chemicals, and its tendency to adhere to most surfaces upon polymerization. Two micromachining routes, both utilizing semiconductor-based lithography techniques, have been developed: microcasting and direct photopolymerization. These are described in the following sections. The resulting polymer structures obtained may be used directly, or may undergo the polymer-to-ceramic transformation.

2.2.1 Microcasting:

In this approach, shown in Figure 4, the liquid precursor is cast into micromolds, polymerized, and demolded. The micromolds are made by standard UV-lithography of the commercial epoxy-resin photoresist SU8^{TM} (from Micro Chem Corp) and may range in depth from 5 to over 100 microns (a - b), with silicon as the handling wafer. Due to the polysilazane's tendency to adhere strongly to almost any surface it contacts upon polymerization, the entire wafer and mold are coated with a thin conformal Teflon layer (from Dupont) which is applied by spin-coating and baking (c). The liquid precursor is then spun onto the wafer, but due to the hydrophobic Teflon-coated top mold surface, the liquid tends to accumulate only in the cavities, leaving a cleanly-filled mold that does not require polishing (d – f). The filled mold is then exposed to UV, which solidifies the precursor by free-radical photopolymerization (g). Alternatively, the precursor could be polymerized thermally by heating at 140 ^oC. The solid preceramic structures are then demolded by heating the wafer in an oven at 250 ^oC. The thermal expansion mismatch between the SU8^{TM} mold and the silicon wafer causes the SU8^{T}M layer to separate cleanly from the wafer, leaving behind free-standing polymer structures. These polymer structures are then crosslinked and may be pyrolyzed if so desired.

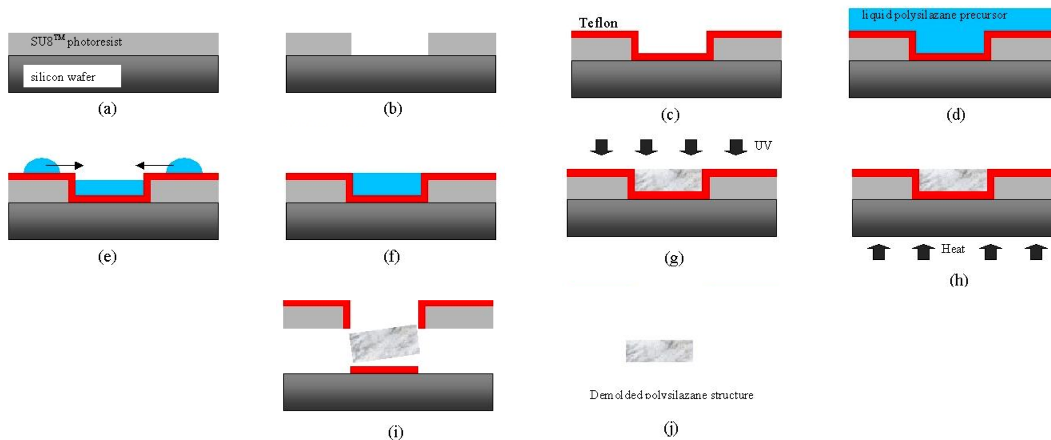

Figure 4. The microcasting process.

2.2.2 Direct Photopolymerization

If a photoinitiator is added to the liquid precursor, the preceramic polymer can be polymerized by exposure to UV rather than by heat addition. This enables one to photolithographically pattern the preceramic polymer as if it were a negative photoresist, see Figure 5. The photoinitiator we use is 2,2 dimethoxy-2-phenyl acetophenone. The glass photomask is first coated with a layer of Teflon, and then placed in contact with the precursor and exposed. Following exposure, the unpolymerized liquid is rinsed away in acetone, leaving behind polymerized structures on the silicon wafer. These structures are then released from the wafer either by scraping with a surgical blade, or by etching away the silicon using XeF_2 gas (wet etchants for silicon have proven to adversely affect the polymer, wherease XeF_2, due to its high selectivity to silicon, does not). These polymer structures can then be crosslinked and pyrolyzed.

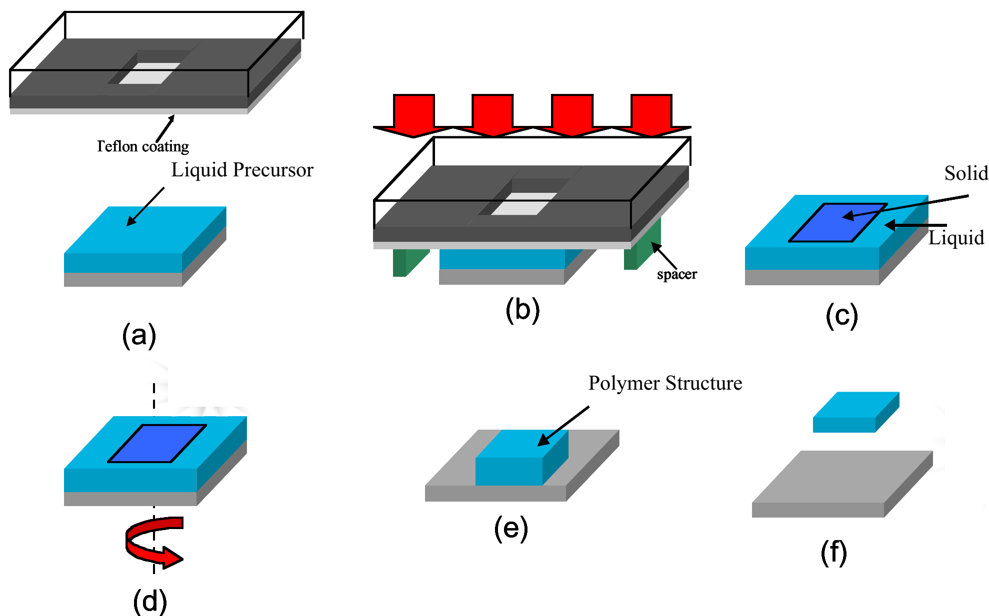

Figure 5. The direct photopolymerization method.

We have so far accomplished device-level and chip-level (“zero”- and “first”- level) packaging of PDC MEMS devices. One substantial drawback to the current PDC MEMS technology is that devices have to be released from the substrate during fabrication to accommodate the substantial shrinkage during the polymer-to-ceramic transformation. As a result, the final ceramic devices are free-standing components, independent of any wafer or die. Wafer-level packaging is thus currently not feasible, which is a significant disadvantage for MEMS commercialization. The closest approximation to wafer-level packaging is accomplished by fabricating arrays of tether-connected devices which, when collectively released from the substrate, can be simultaneously packaged and then disconnected from one another by breaking the tethers. An exception is the use of certain types of polymer devices, since the polymer structures may remain on the wafer.

Unless the devices themselves are microfluidic channels [19] which are chips in and of themselves, the present procedure for packaging PDC MEMS starts with fabricating a wafer or substrate containing bond pads and electrical traces, independently from the PDC devices. Such a wafer is typically silicon or alumina, due to the commercial availability of such microelectronic substrates in prototyping quantities. The wafer is patterned and diced into individual chips, then the MEMS devices are then assembled on each substrate using flip-chip [14], manual or robotic pick-and-place techniques. These techniques constrain the devices' minimum design size to roughly tens of microns so that the devices will be robust enough for such assembly methods. Indium solder (deposited on the substrate bond pads by evaporation and lift-off techniques) or silver paint epoxy have been used to mechanically and electrically connect the PDC MEMS devices to the substrate. The chips are then wirebonded to ceramic dual-in-line packages for connection to external electrical signals.

Because the materials used – other than the SiCN devices themselves – are not refractory, these packaging techniques are not suitable for high-temperature/harsh-environment applications. If the MEMS is refractory but the package is not, the purpose of fulfilling harsh environment applications is defeated. An exception, such as in the case of the Micro-Igniter, is when the high-temperatures are extremely localized within the PDC device itself.

Harsh-environment MEMS packaging is presently a young and technically challenging field. Recent advances in silicon carbide MEMS/semiconductor technology have shown the maximum global operating temperature of SiC devices to be around 600 ^{o}C [20], the limiting factor being degradation of the electrical contacts [21] rather than the device itself. In light of this, our group is also developing high-temperature electrical interconnects that are compatible with the PDC process. TiN appears to be a promising low contact-resistance interconnect material that is stable up to at least 1430 ^{o}C in argon and which is formed from the reaction between SiCN and Ti [22].

3. POLYMER DEVICE: A GRATING

In addition to the remarkable properties of PDC-SiCN, it is worthwhile to note the polymeric precursor to SiCN, polysilazane, is itself a novel engineering material for MEMS. A simple phase transmission grating was fabricated to demonstrate how this novel transparent polymer may be used in an optical MEMS application [19].

Polysilazane is a novel hybrid organic/inorganic polymeric glass that is highly transparent in the infrared to ultraviolet range and exhibits thermal stability superior to that of organic glasses such as polycarbonate and PMMA at temperatures up to 230 oC without losing optical transparency [18]. In addition, the UV absorption of the polysilazane is closer to that of silicate glass than to pure organic polymeric glasses. Li et al [18] have shown that when PUMVS is cross-linked at 260 ^{o}C, in a flowing gas atmosphere of 10 sccm in Ar or N_2 for 2 hours, polysilazane structures exhibit a high degree of transparency within a broad wavelength range between 1450 nm (infrared) and 300 nm (ultraviolet). The ultraviolet absorption edge of cross-linked polysilazane is 300 nm, which is close to that of Durobax (280 nm), and beyond the absorption edges of Makrolon (400 nm), and Plexiglas (370 nm). Furthermore, cross-linked polysilazane shows relatively good thermal stability and remains highly transparent (~80% transmittance) within these wavelengths after

heat treatments of 1 hour at 230 oC in air while Makrolon melted, and Plexiglas showed significant decomposition. Its mechanical properties were reported as having Vicker's Hardness of 120 MPa, while Makrolon and Plexiglas exhibit Vicker's Hardness' of 130 and 200 MPa, respectively [18]. Figure 7 shows visually shows the optical transparency of polysilazane MEMS structures compared to a glass slide [19].

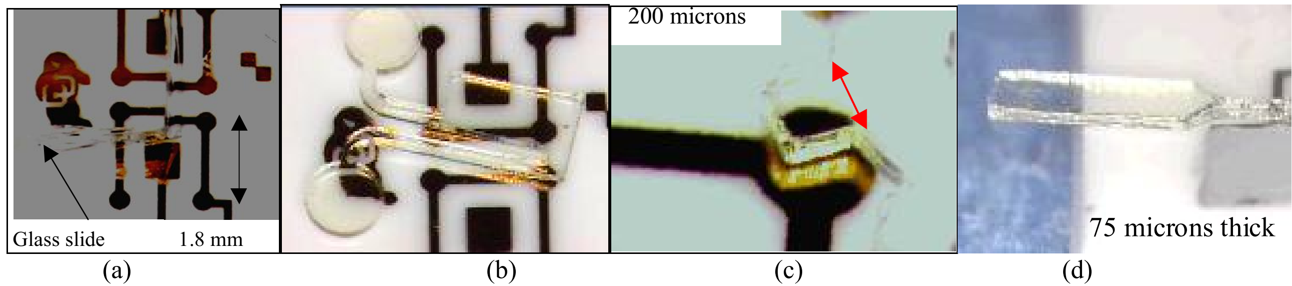

Figure 7. A microscope glass slide placed on an alumina substrate with a patterned C.U.-Buffalo micro-logo for optical transparency comparison with (b), (c) and (d) (b) Polysilazane structure; each polysilazane circle is 790 microns in diameter. Structures is 75 microns thick. (c) Closeup of the gear(60 microns thick) shown in Figure 2(a). (d) Micro tensile-test specimen.

Optical transmission gratings were fabricated from the polysilazane using Microcasting in double-layered SU8^{TM} molds. Most of the gratings exhibited slight curvature of the base plate surface due to surface-tension effects during casting, visible under a microscope. No polishing was performed on any surfaces. Figure 8 shows photographs of one such fabricated grating.

The width of each grating element is 100 microns, and the gap between elements is about 50 microns (thus the pitch is 150 microns). The height of the elements (or groove depth) is about 40 microns, and the thickness of the base plate is about 75 microns. Compared to gratings made commercially or by other technologies, this grating is very coarse, the line dimensions being one or two orders of magnitude greater. Much finer features are possible with carefully controlled cleanroom processing and the use of higher resolution photomasks. In this case, since only a demonstration device was intended without a specific application, feature sizes were increased for ease of fabrication. Furthermore, because polishing was not performed in this case, the surfaces of the grating are not as smooth as that of glass gratings, although in principle polishing could be added to smooth and planarize the surfaces.

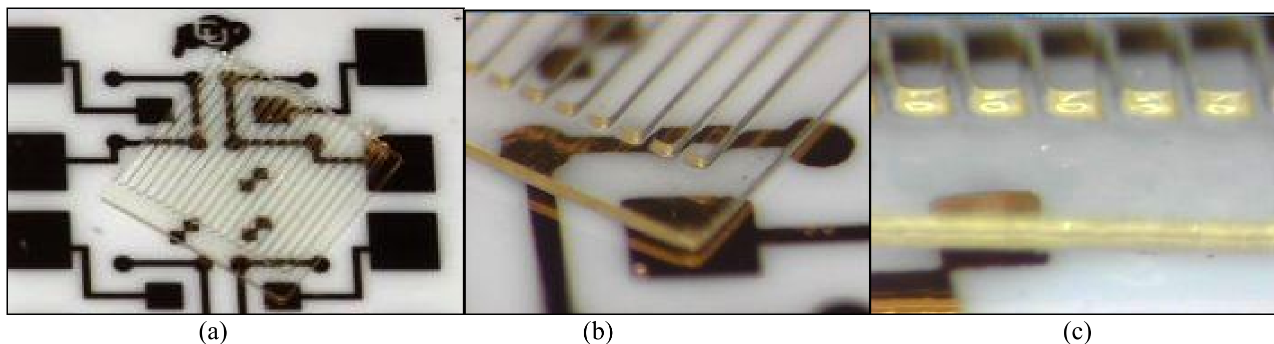

Figure 8. Photographs of polysilazane transmission grating, placed on a piece of alumina with arbitrary gold patterns. Entire grating is 3mm x 3m. (b) and (c) show closeups of the grating grooves.

To demonstrate their high-temperature effectiveness, the gratings were placed in an oven at 250 ^{o}C for several minutes prior to testing. PMMA and polycarbonate material samples that were placed in the same oven partially melted or degraded.

The gratings were then tested by simply passing a laser through the device and observing the diffraction pattern. A grating was mounted to the edge of a glass slide using double-sided tape so that most of the grating was suspended in air, as shown in Figure 9(a). The glass slide was then attached to a x-y-z optical stage. A He-Ne laser beam (wavelength 632 nm) was passed through a beam expander and collimating lens, before passing through the grating at an angle that was normal to its plane. A typical diffraction pattern resulted on a white screen placed some distance in front of the grating, as shown in Figure 9(b). Figure 9(c) shows the measured grating efficiency.

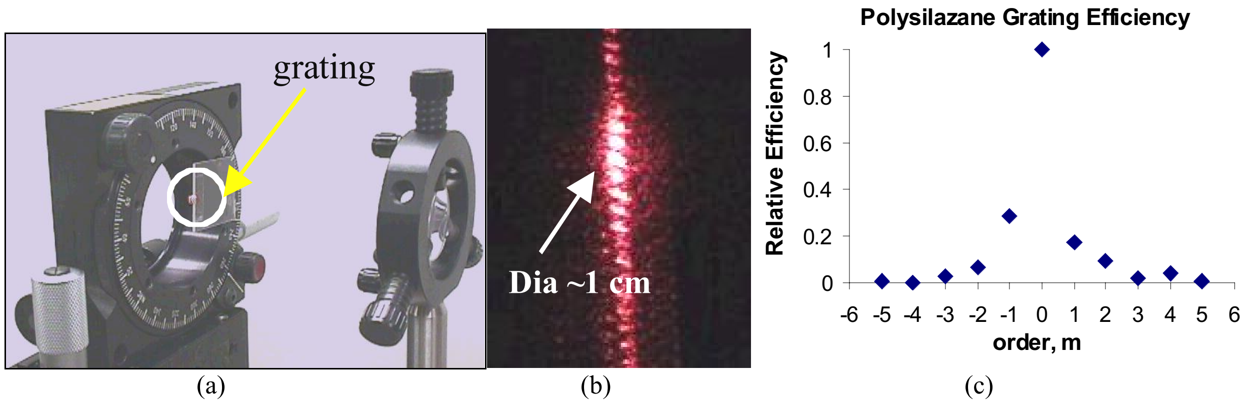

Figure 9(a) Closeup of the mounted grating. The laser spot is focused on the grating. (b) Resulting diffraction pattern. (c) Relative efficiency for each diffracted order, for wavelength of 632 nm.

Grating efficiency can be improved by use of higher resolution photomasks and refined cleanroom processing to reduce line widths, by polishing the grating surfaces to achieve smoother and more planar surfaces, and by controlling the incident beam angle more carefully to obtain more accurate efficiency measurements.

Since the incident beam was normal to the back plane of the grating (i.e. incident angle = 0), the grating equation simplifies to [23]:

$$P \sin \lambda m = m\lambda$$

where P is the pitch of the grating (in this 150 microns), m is the order of diffraction, and λ _is the wavelength of the incident beam. Thus the expected angle of the first diffracted order (m = 1) was calculated from this equation to be about 0.24 ^{o} from the normal. By measuring the distance between the m=0 and m=1 spot (about 1.2 cm), and measuring the distance between the screen and the grating (about 10 feet), the experimental diffraction angle was computed to be about 0.21 ^{o}, which is in good agreement with the predicted angle.

We have thus demonstrated a low-cost micromachined phase transmission grating that is operational following heating in 250 ^{o}C environment.

3. CERAMIC DEVICE: MICRO IGNITER

In contrast to the transparent polymer-glass, the pyrolyzed version of material is a lustrous black-colored bulk ceramic which is also a high-temperature semiconductor. We have exploited the refractory and semiconductive properties of SiCN in realizing a micro igniter for applications requiring ultrahigh-temperature thermal ignition.

3.1 Design, Fabrication, Packaging of Micro Igniter

An example of a high-temperature ceramic MEMS device from this material system is a micro igniter which we call a "Micro Glow Plug" [24, 25], shown in Figure 10. It measures about 1 mm in length and its resistively-heated tip has been measured at 1550 ^{o}C for over 10 days of continuous operation in air. This is, to our knowledge, the highest temperature achieved by a MEMS heater. It is composed of a single layer of SiCN that has been annealed to make it electrically conductive at room-temperature. The cross-section of the U-shaped device is designed to be about 10 times smaller at the tip compared to that of the arms, thus the higher current density in the tip results in resistive heating while the wider arms remain relatively cool due to the low thermal conductivity of SiCN. For example, when the tip temperature is measured at 1000 ^{o}C, the temperature of the bond pads is only 200 ^{o}C. Thus, this highly localized heating allows for packaging using common integrated circuit packaging methods such as the use of alumina die, gold metal interconnects and wirebonds, and silver epoxy die attach.

The Micro Glow Plugs are batch fabricated using from the polysilazane precursor using Direct-Photopolymerization technique followed by crosslinking, pyrolysis and annealing the in a hot isostatic press. They are then individually assembled, using silver epoxy, onto a custom-fabricated alumina receiving substrate which contains patterned gold bond pads and electrical traces. The die is then packaged and wirebonded to a standard 40-pin dual in line ceramic package which allows standard electrical inputs and outputs.

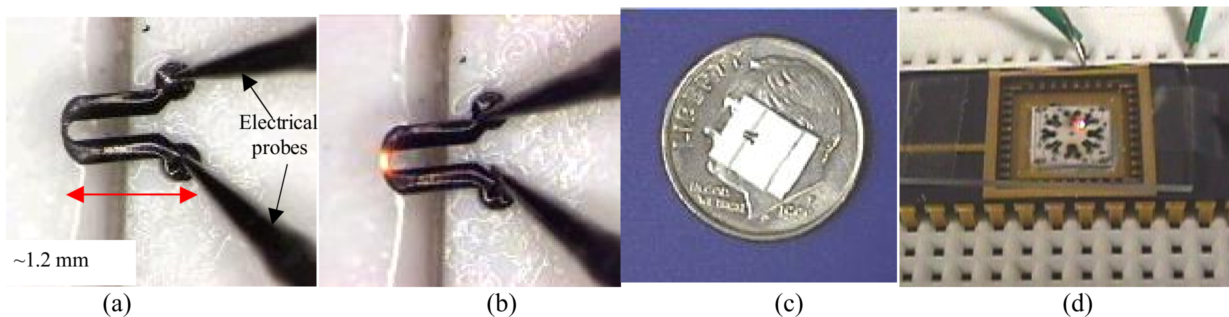

Figure 10. (a) Photograph of the Micro Glow Plug in the "off" state and (b) in the "on" state. (c) Photograph of a single device on a U.S. dime, (d) photograph of an array of 8 devices, with one device activated.

3.2 Model and Experiment

Packaged arrays of devices were characterized according to their electro-thermal behavior to obtain fundamental material properties and to demonstrate the application as an ultrahigh temperature igniter. Each device was given a constant d.c. current and a LabView data acquisition program was used to record their electrical resistivity over time and for different current inputs. The tip (or "web") temperature was measured using K-thermocouples and a pyrometer. All experiments were done in air.

Figure 11(a) shows a typical device's resistivity as a function of temperature from resistive heating [25]. This linear relationship indicates that the SiCN material follows Mott's Variable Range Hopping (VRH) mechanism for amorphous semiconductors [26], which is in agreement with studies by Haluschka et al [9] and Hermann et al [10], who found this behavior to extend up to at least 1000 ^{o}C. From this data, fundamental semiconductive properties for SiCN such as the Mott parameters can be obtained directly from the device in-situ.

Once the semiconductive properties have been determined from Figure 11(a), the web temperature can be modeled reasonably well using a lumped heat transfer analysis, see Figure 11(b) [25]. From a device perspective this enables one to predict the required power to achieve a desired web temperature. The temperature measurements in Figure 11 were obtained using a K thermocouple, which melted above 1400 ^{o}C. Subsequent measurements with a pyrometer have

indicated that the devices to maintain a web temperature of 1550 °C for over 10 days of continuous operation (d.c. mode) in air.

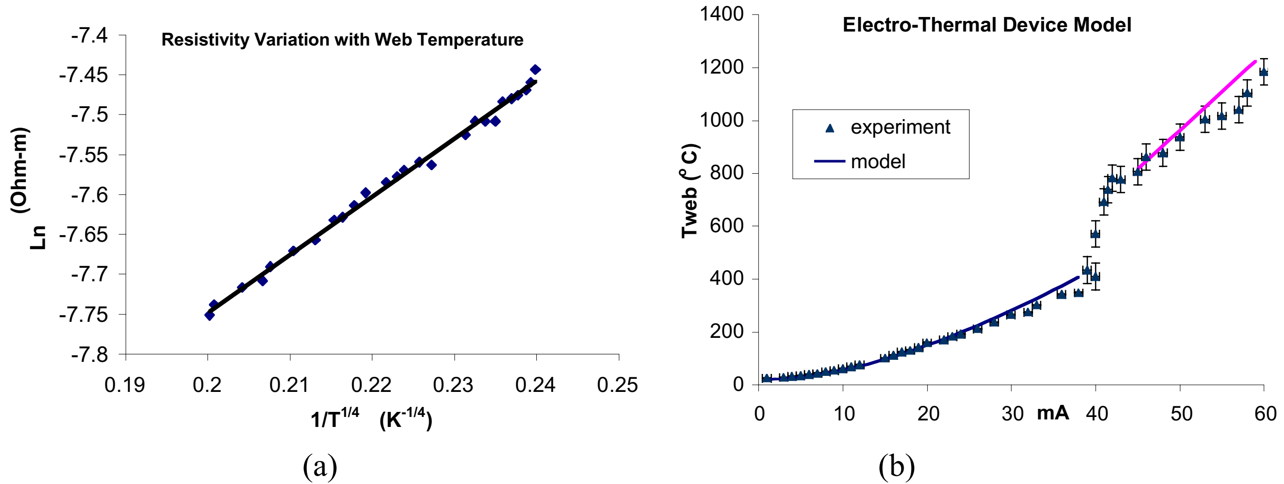

Figure 11. (a) SiCN resistivity versus temperature, as obtained from the MGP, indicating the Mott VRH mechanism. (b) Modeled and measured temperatures of the micro igniter tip as a function of applied current.

The device lifetime was also measured as a function of applied current and web-temperature. From this, one can obtain the fundamental oxidation activation energy and rate constants for SiCN.

Such ultrahigh-temperature micro heaters can find immediate application in the young but growing field of micro power generation – for example as igniters for power generation schemes based on combustion of hydrocarbons. In fact, the micro combustion chamber itself could feasibly be made from SiCN [14]. Alternatively, MEMS igniters could function as smaller, lighter and cheaper alternatives to current macro-sized igniters for traditional applications such as diesel engine ignition. Table 2 compares the key operating features of a conventional diesel engine glow plug with that of the MGP.

	Conventional Glow Plugs	**SiCN Micro Glow Plug**
Size	Length 30-50 mm	Length 1.1 mm
Temperature	1200 °C	1200 °C
Power Consumption	100 Watts	3 Watts
Response Time	5-10 seconds	0.5 second
Fabrication Complexity	3 materials 3 processes	1 material 1 process

Table 2. Comparison between conventional diesel glow plugs and the Micro Glow Plug.

4. HUMAN-MACHINE INTERFACE

Another unique feature of the work at University of Colorado at Boulder in PDC MEMS is the development of a new computational methodology that unites fundamental materials science, mechanical design, reliability analysis, and system level performance in a seamless interactive environment. We call this environment the Human-Machine Interface (HMI) [27]. The HMI serves as a real time display of device performance, and reliability assessment. The experimental system for the HMI is the SiCN Micro Igniter.

The HMI is a methodology. It can be visualized as an “operating system” which serves as a platform for interactive design, optimization, and reliability analysis, with intimate coupling to the science of novel materials. The HMI is not only a simulation platform but also a real-time interface which provides information on the performance, the status and the remaining life of “materials-critical” device(s) in the system.

The development of the “ab-initio” HMI implies the integration of fundamental equations that originate from atomistic understanding of material behavior, directly into the analysis of the performance and the design of the system. The underlying concept is that the engineering analysis should be transparent to the scientist, and the scientific limitations transparent to the engineer. This is the ab-initio system-integration approach, which is being aggressively pursued at the University of Colorado. Figure 12 shows a schematic of the HMI concept, and a simulation of the Micro Igniter’s resistance change over time as a result of a constant d.c. current input [27].

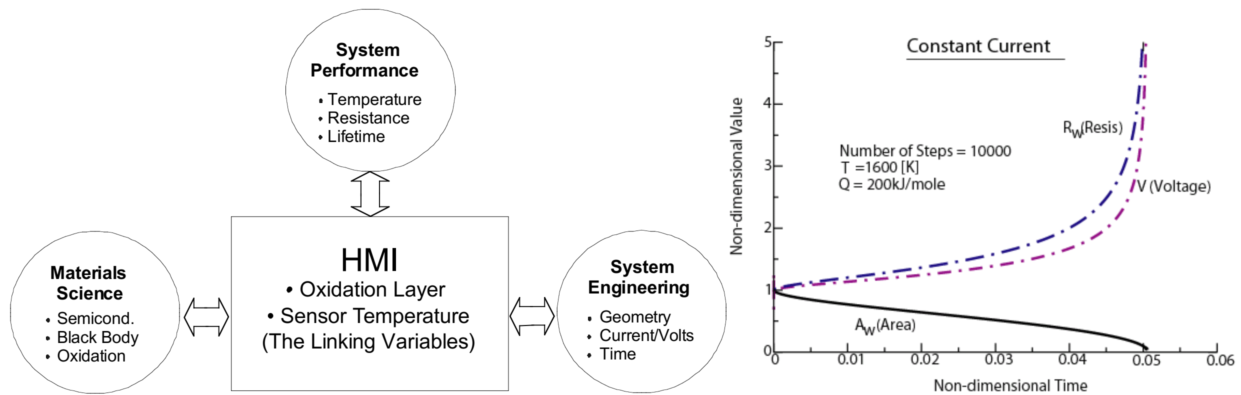

Figure 12. Concept of the Human-Machine Interface, and a resulting simulation of the Micro Igniter’s resistance change over time from a constant current input.

CONCLUSION

Polymer-derived ceramics (PDCs) are a new class of amorphous, multifunctional and highly refractory ceramics derived from liquid polysilazanes, which in themselves are novel refractory polymer-glasses. Our group has conducted exploratory research into the science and technology of PDCs with emphasis on MEMS applications, and have shown that PDCs are viable and promising materials for low-cost harsh-environment MEMS. The dual nature of this material system is demonstrated in examples of polymer and ceramic MEMS devices: a polymer transmission grating that remains functional following 250 ^{o}C exposure in air, and a micro igniter which has operated at 1550 ^{o}C for over 10 days in air. This is, to our knowledge, the highest-temperature achieved to date by a MEMS heater. Thus, the advantage of high refractory properties combined with low-cost polymer processing makes PDC MEMS ideally suited for high-temperature and harsh environment applications where current MEMS technology is limited. In addition, a novel computational methodology integrating materials science with design, optimization and reliability analysis, known as the Human-Machine Interface, has been developed with the Micro Igniter as a representative experimental system.

ACKNOWLEDGEMENTS

This work is supported by the Defense Advanced Research Projects Agency (DARPA) and U.S. Air Force under contract # F30602-99-2-0543, and Air Force Office of Scientific Research, USAF, under grant number F49620-01-1-052.

REFERENCES

1. D.M. Burns and V.M. Bright, “Optical Power Induced Damage to Microelectromechanical Mirrors,” Sensors and Actuators, A, **70**, pp. 6-14, 1999.

2. M. Mehregany and C.A. Zorman, “SiC MEMS: Opportunities and Challenges for Applications in Harsh Environments,” Thin Solid Films, **355-356**, pp. 5180524, 1999.

3. U. Kaufmann, J. Haubelt, H. Moritz, “Fast Fabrication of Ceramic Microcomponents,” MST News, No. 4/01, pp. 35-38, Sept 2001.

4. J.M. English and M.G. Allen, “Wireless micromachined ceramic pres-sure sensors” Proceedings of the Twelfth IEEE International Conference on Microelectromechanical Systems *(MEMS 99)*, Orlando, Florida, 17-21 January, 511–516, 1999.

5. R. Raj, R. Riedel and G. D. Soraru, “Ultrahigh Temperature Polymer Derived Ceramics”, J. Amer. Ceram. Soc., **84**[10], 2158-59 (2001).

6. R. Riedel, G. Passing, H. Sch¨ onfelder, and R.J. Brook, “Synthesis of Dense Silicon-Based Ceramics at Low Temperature” *Nature*, **355**, pp. 714–716, 1992.

7. R. Raj, L. An, S. Shah, R. Riedel, C. Fasel and H.-J. Kleebe, “Oxidation Kinetics of an Amorphous Silicon Carbonitride Ceramic*”,* J. Amer. Ceram. Soc., **84**[8], 1803-10 (2001).

8. L. An, R. Riedel, C. Konetschny, H. -J. Kleebe and R. Raj, “Newtonian Viscosity of Amorphous Silicon Carbonitride at High Temperatures”, J. Amer. Ceram. Soc., **81**[5], 1349-52, 1998.

9. C. Haluschka, C. Engel and R. Reidel, “Silicon Carbonitride Ceramics Derived From Polysilazanes, Part II: Investigation of Electrical Properties,” J. European Ceramic Society, **20**, pp. 1365-1374, 2000.

10. P.A. Ramakrishnan, T.-T. Wang, D. Balzar, L.An, C. Haluschka, R. Riedel and A.M. Hermann, “Silicoboron-Carbonitride Ceramics: A Class of High-Temperature, Dopable Electronic Materials,” Applied Physics Letters, **78**[20], pp. 3076-3078, 2001.

11. H. Yang, P. Deschatelets, S.T. Brittain, and G.M. Whitesides, “Fabrication of high performance ceramic microstructures from a polymeric precursor using soft lithography,” Advanced Engineering Materials, **13**[1:54–58], 2001.

12. Hanemann T, Ade M, Borner M, Motz G, Schulz M, Hausselt J, "Microstructuring of Preceramic Polymers, Adv. Engrg Mater., **4**[11], pp. 869-873, NOV 2002.

13. L. Liew, W. Zhang, Linan An, S. Shah, R. Lou, Y. Liu, T. Cross, K. Anseth, V. Bright, J. W. Daily and R. Raj, “Ceramic MEMS - New Materials, Innovative Processing and Future Applications”, Am. Cer. Soc. Bulletin, **80**[5], 25-30, May 2001.

14. L.A. Liew, Y. Liu, R. Luo, T. Cross, L. An, V. M. Bright, M. L. Dunn, J. W. Daily and R. Raj, “Fabrication of SiCN MEMS By Photopolymerization of Pre-Ceramic Polymer,” Sensors and Actuators, **A-95**[2-3], pp. 120-134, 2002.

15. R.A. Saravanan, L. A. Liew, V.M. Bright and R. Raj, “Integration of Ceramics Research with the Development of a Microsystem,” to be published in J. American Ceramic Society, Accepted December 2002.

16. L.A. Liew, R.A. Saravanan, V.M. Bright and R. Raj, “Processing and Characterization of Silicon Carbon-Nitride Ceramics: Application of Electrical Properties Towards MEMS Thermal Actuators,” to be published *in Sensors and Actuators, A*. Accepted June 2002.

17. T. Cross, L.A. Liew, V.M. Bright, M.L. Dunn, J.W. Daily and R. Raj, “Fabrication Process for Ultra High Aspect Ratio Polysilazane-Derived MEMS,” *Proceedings of the 15th Annual International Conference on Micro Electromechanical Systems (MEMS2002*), pp. 172-175, Las Vegas, Nevada, Jan 20-24, 2002.

18. Li, Y.-L., Riedel, R., Steiger, J., Seggern, H.v., “Novel Transparent Polysilazane Glass: Synthesis and Properties,” *Advanced Engineering Materials*, vol. 2 no. 5, pp. 290-293, 2000.

19. L.A. Liew, T. Cross, V.M. Bright and R. Raj, “Fabrication of Novel Polysilazane MEMS Structures by Micro Casting,” *Proceedings of the 2001 ASME International Mechanical Engineering Congress and Exposition (IMECE 2001*), CD-Vol.2, No. MEMS-23920, New York, NY, Nov 11-16, 2001.

20. R. S. Okojie, A. A. Ned, A. D. Kurtz, W. N. Carr, “Electrical characterization of annealed Ti/TiN/Pt contacts on N-type 6H-SiC epilayer”, IEEE Trans. on Electron Dev., **46**[2], pp. 269-274 (1999).

21. R. S. Okojie, D. Spry, J. Krotine, C. Salupo, and D. R. Wheeler, "Stable Ti/TaSi2/Pt Ohmic Contacts on N-Type 6H-SiC Epilayer at 600C in Air", *in Materials Research Society Symposia Proceedings*, vol. 622, Wide-Bandgap Electronic Devices, R. J. Shul, F. Ren, M. Murakami, and W. Pletschen, Eds. Warrandale, PA: Materials Research Society, 2000.

22. H.Y. Ryu, R.A. Saravanan and R. Raj, “TiN Coating – A Solution for High-Temperature Interconnects*,” Proceedings of the 35th International Symposium on Microelectronics (IMAPS 2002)*, International Microelectronics and Packaging Society, Denver, CO, September 4-6, pp. 490-493, 2002.

23. E. Hect. Optics, 2nd Ed. Addison-Wesley Publishing Company, MA, 1990.

24. L.A. Liew, V.M. Bright and R. Raj, “A Novel Micromachined Glow Plug for Ultrahigh Temperature Ignition Applications,” *Proceedings of the 2002 Solid-State Sensor, Actuator and Microsystems Workshop (Hilton Head 2002),* June 2-6, Hilton Head Island, South Carolina, pp. 243-246, 2002.

25. L.A Liew, V.M. Bright and R. Raj, “A Novel Micro Glow Plug Fabricated from Polymer-Derived Ceramics: In-Situ Measurement of High-Temperature Properties and Application to Ultrahigh Temperature Ignition,” to be published in *Sensors and Actuators, A*. Accepted August 2002.

26. N.F. Mott, “Conduction and switching in non-crystalline materials,”*Contemporary Physics*, vol. 10, pp. 125–138, 1969.

27. J. Kong, K. Maute, D. Frangopol, L.-A. Liew, R. A. Saravanan, V. M. Bright, and R. Raj, “A Real Time Human Machine Interface for an Ultrahigh Temperature MEMS Sensor-Ignitor,” Sensors and Actuators, in press, February 2003.