

Lithography and Etching-Free Microfabrication of Silicon Carbide on Insulator Using Direct UV Laser Ablation

Tuan-Khoa Nguyen,* Hoang-Phuong Phan, Karen M. Dowling, Ananth Saran Yalamarthy, Toan Dinh, Vivekananthan Balakrishnan, Tanya Liu, Caitlin A. Chapin, Quoc-Dung Truong, Van Thanh Dau, Kenneth E. Goodson, Debbie G. Senesky, Dzung Viet Dao, and Nam-Trung Nguyen

Silicon carbide (SiC)-based microsystems are promising alternatives for silicon-based counterparts in a wide range of applications aiming at conditions of high temperature, high corrosion, and extreme vibration/shock. However, its high resistance to chemical substances makes the fabrication of SiC particularly challenging and less cost-effective. To date, most SiC micromachining processes require time-consuming and high-cost SiC dry-etching steps followed by metal wet etching, which slows down the prototyping and characterization process of SiC devices. This work presents a lithography and etching-free microfabrication for 3C-SiC on insulator-based microelectromechanical systems (MEMS) devices. In particular, a direct laser ablation technique to replace the conventional lithography and etching processes to form functional SiC devices from 3C-SiC-on-glass wafers is used. Utilizing a single line-cutting mode, both metal contact shapes and SiC microstructures can be patterned simultaneously with a remarkably fast speed of over 20 cm s^{-1} . As a proof of concept, several SiC microdevices, including temperature sensors, strain sensors, and microheaters, are demonstrated, showing the potential of the proposed technique for rapid and reliable prototyping of SiC-based MEMS.

owing to its superior physical properties and resilience over Si in harsh environmental applications.^[1–3] The advantages result from the high energy bandgap, mechanical strength, chemical inertness, and the high melting point of SiC.^[4–6] Therefore, a wide range of SiC-based microsensing/electronics devices have been developed with several micromachining techniques.^[7,8] Unlike silicon counterparts, SiC micromachining processes are undoubtedly limited and expensive due to the chemical inertness of SiC. For instance, SiC wet-etching processes typically requires extreme conditions and aggressive chemicals.^[9] Moreover, in terms of patterning bulk SiC wafers, dry etching of SiC using plasma-based processes results in a very low etching rate, hindering the implementation of SiC micro/nanoelectronic and sensing devices on a large scale. To mitigate this obstacle, epitaxially grown SiC on silicon substrates has been introduced and proven to be a promising approach because it only

requires patterning of thin SiC layers and therefore is more favorable than approaches using bulk SiC wafers. Compared with other polytypes such as 4H-SiC and 6H-SiC, the cubic SiC is the most suitable polytype for microsensing applications.

1. Introduction

Silicon carbide (SiC) has been attracting a significant interest from the microelectromechanical systems (MEMS) community

Dr. T.-K. Nguyen, Dr. H.-P. Phan, Dr. T. Dinh, Dr. V. Balakrishnan, Prof. N.-T. Nguyen
Queensland Micro and Nanotechnology Centre
Griffith University
170 Kessels Road, Brisbane, Queensland 4111, Australia
E-mail: k.nguyentuan@griffith.edu.au

K. M. Dowling, A. S. Yalamarthy, Prof. D. G. Senesky
Department of Electrical Engineering
Stanford University
350 Jane Stanford Way, Stanford, CA 94305, USA

Dr. T. Dinh
School of Mechanical and Electrical Engineering
University of Southern Queensland
West St, Darling Heights, Queensland 4350, Australia

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adem.201901173>.

DOI: 10.1002/adem.201901173

T. Liu, Prof. K. E. Goodson
Department of Mechanical Engineering
Stanford University
Building 530, 440 Escondido Mall, Stanford, CA 94305, USA

C. A. Chapin, Prof. D. G. Senesky
Department of Aeronautics & Astronautics
Stanford University
496 Lomita Mall Durand Building, Stanford, CA 94305, USA

Q.-D. Truong
R&D Center
BOSCH Automotive
Deutsches Haus, 33 Le Duan, Ben Nghe, Ho Chi Minh, Vietnam

Dr. V. T. Dau, Prof. D. V. Dao
School of Engineering and Built Environment
Griffith University
Parklands Drive, Gold Coast, Queensland 4215, Australia

This is owing to its capability of deposition on a Si substrate, making it compatible with MEMS processes as well as reducing the cost of the material compared with the bulk counterparts. In addition, this platform can benefit from the mature Si-based fabrication processes such as etching of the Si substrate, making it convenient for engineering SiC-based microsystems. Due to technological developments in the growth process of SiC on Si, high-quality and large-scale epitaxial SiC on Si wafers have been introduced.^[10] However, the leakage of the electric current through the SiC–Si junction drastically increases with temperature, exposing a significant limitation for high-temperature applications that SiC materials are used for. To overcome this obstacle, the SiC thin film can be bonded onto insulating substrates such as glass by wafer bonding to prevent current leakage at high temperature.^[11–13] This platform provides a feasible development for SiC electronics, eliminating the leakage observed in SiC-on-Si electronics at high-temperature operations. Previously, we introduced an anodic bonding technique for as-grown SiC-on-Si onto an insulating substrate (i.e., glass), indicating a great potential for SiC-based sensors and electronics for a wide range of application including biological utilizations.^[11]

To achieve SiC micro/nanostructures, expensive micro/nanomachining processes in tightly controlled cleanroom environments are typically required,^[14] which include lithography processes followed by plasma/wet etching of SiC micro/nanostructures. These strict requirements are significant obstacles for the development of cost-effective SiC-based sensors and electronics devices, hindering the fundamental characterization of the SiC materials. The present work reports a novel method for rapid prototyping of SiC microscale sensors and electronics using UV laser ablation, to extend the application potential of the 3C-SiC-on-glass platform. We demonstrate that the proposed technique can be used to fabricate multifunctional SiC microdevices including temperature/force sensors as well as integrated heaters, which can work at elevated temperatures. The simplified method eliminates sophisticated lithography and etching processes with cleanroom facilities, showing the potential of reducing the fabrication cost of SiC-based microscale sensors and electronics. This approach paves the way for fast-prototyping and cost-effective SiC-based microsensing and heating devices for harsh environmental applications.

2. Lithography and Etching-Free Fabrication of 3C-SiC-on-Glass

Figure 1 shows the concept of the fabrication process using laser ablation starting from a 3C-SiC-on-glass wafer. SiC films were initially epitaxially grown on (100) Si wafers by a low pressure chemical vapor deposition (LPCVD) process and doped with nitrogen to achieve n-type SiC. In our previous work, we have reported that the as-grown SiC film on a Si wafer is single crystalline 3C-SiC and its crystallographic orientation is (100) by selected area diffraction (SAD) and X-ray powder diffraction (XRD) measurements, respectively.^[15] Due to the mismatch in lattice constant and thermal expansion of SiC and Si, we observed the stacking fault defects at the SiC/Si interface. However, the stacking faults are mainly distributed within 50 nm from the SiC/Si interface and the crystallinity significantly

improved with increasing SiC film thickness. The carrier concentration of the SiC thin film was measured to be 10^{18} cm^{-3} by a hot-probe technique. The resistivity of the SiC film was $8 \Omega \mu\text{m}$. Subsequently, the as-grown 600 nm SiC thin films were transferred onto an insulating substrate by anodic bonding. The details of the transferring process of SiC onto an insulating substrate can be found elsewhere.^[11]

Next, a 200 nm nickel (Ni) layer was selectively deposited on top of the 600 nm SiC layer using a shadow mask, forming a Ni layer only in desired electrode areas (**Figure 1c**). Micropatterns of SiC were then formed by laser scribing with a diode-pumped solid state (DPSS) Samurai laser (355 nm wavelength) at an average power of 2 W. The Ni layer was also cut to confine the metal electrode pads. The cutting mode for both SiC and Ni was chosen as single-cut lines at 50% of the full power setting ($\approx 3 \text{ W}$) with a scanning speed of 200 mm s^{-1} , forming trenches on the glass substrate, which electrically isolates SiC devices from each other. The SiC microstructure designs, created using a standard computer-aided design (CAD) software, were aligned with the predeposited electrode areas using the printing–preview mode and a home-built camera system. As the laser only etches the boundary (i.e., perimeter) of each SiC microstructure, the total fabrication time is extremely short. For instance, the fabrication of an array of ten SiC U-shape resistors with a total perimeter of 120 mm took less than 5 s. In addition, movable structures of SiC such as one-sided clamped cantilevers or double-sided clamped bridges can also be formed because the UV laser can also remove the glass substrate, enabling rapid prototyping of SiC-based mechanical sensors and electronics. In cleanroom-based fabrication processes, SiC sensors and electrodes are patterned through the deposition/development of photoresist followed by SiC and/or metal etching. In contrast, our direct laser ablation of SiC only requires a single cutting step, which significantly reduces the fabrication time and eliminates material and chemical costs associated with the lithography and etching processes arising from conventional micromachining fabrications. With this new method, the postetching process (e.g., photoresist removal) is no longer required, allowing for the fabrication of SiC-on-glass microelectronics devices in typical laboratory conditions without the need for a cleanroom facility. The fabricated SiC structures can be utilized as a multifunctional sensing and heating platform for numerous applications.

3. Demonstration of Laser-Engraved SiC Applications

As the UV laser radiation can penetrate and remove the SiC thin film and glass layers, it is convenient and cost-effective to form SiC-based sensors/heaters in one single-step fabrication. **Figure 1d–f** shows images of the fabricated SiC structures including text patterns, U-shaped resistors, and a spring-shaped heater on a 3C-SiC-on-glass chip (**Figure 1g**). The current–voltage characteristic of the as-fabricated SiC resistors was measured using a digital multimeter (i.e., Agilent B1500), indicating an excellent Ohmic contact between metal and SiC (**Figure 2**). The resistance of SiC was measured for nine samples, showing a small deviation of less than 5%. This result indicates the uniformity of SiC devices fabricated using a single-step UV laser ablation. Furthermore, as the SiC was transferred onto a glass substrate,

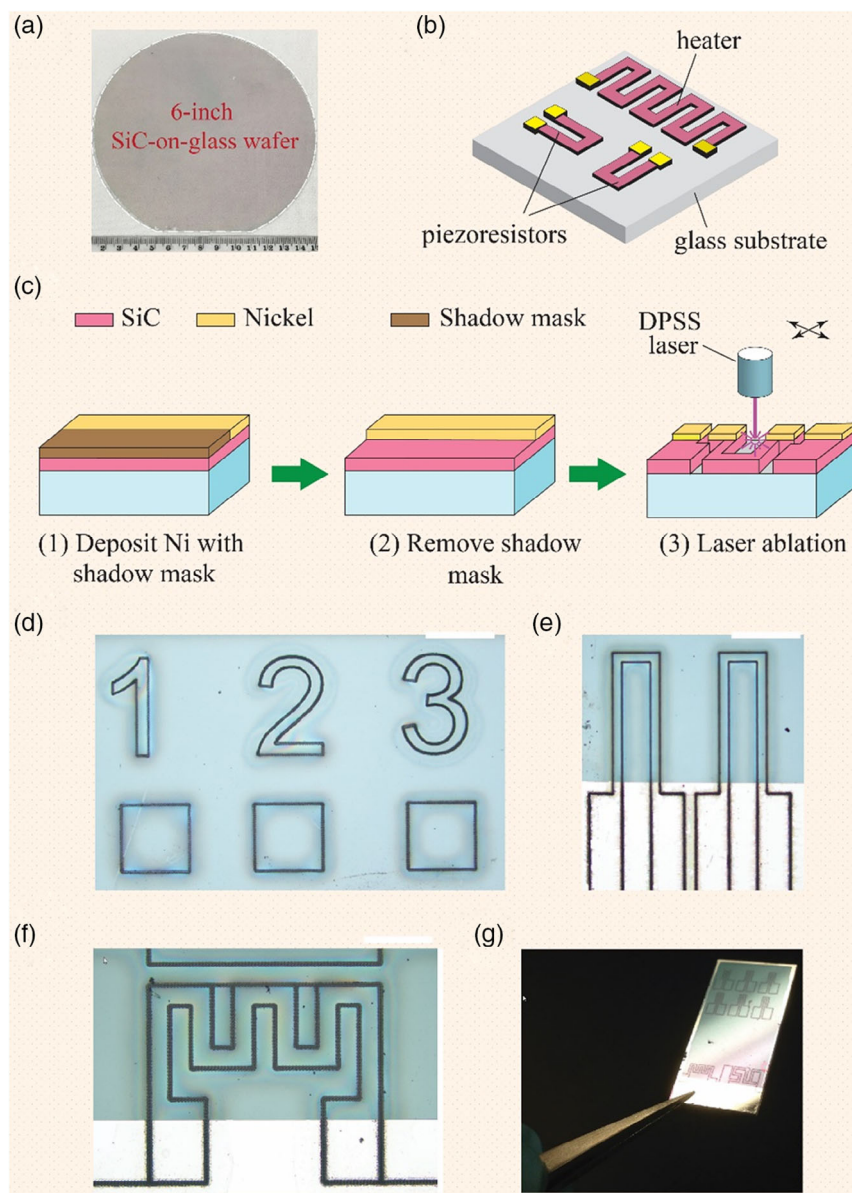


Figure 1. Concept of the lithography-free process to form SiC microdevices. a) Photograph of 6 in. 3C-SiC-on-glass wafer (SiC film was transferred onto glass from a (100) SiC-on-Si wafer). b) Schematic sketch of fabricated structures after direct laser ablation technique. c) Fabrication steps using a shadow mask to form patterned metal contacts, followed by computer-aided control laser ablation to create various patterns of piezoresistors and microheaters. d) Patterned structures from 3C-SiC-on-glass wafer. e) U-shape resistors for temperature and force sensors. f) Spring-shaped microheater; the metal contact areas are shown as white color; scale bar for (d), (e), (f): 500 μm . g) Photograph of multifunctional chip consisting of various types of microscale sensors and heaters using the laser ablation method.

the problem of current leakage into the substrate was completely solved, enabling the development of SiC-based high-temperature sensing devices. The following subsections demonstrate several MEMS applications of our laser ablation technique including temperature sensors, microheaters, and force sensors.

3.1. Temperature Sensors

Owing to its resilience to high temperature and the significant thermoresistive effect, the 3C-SiC-on-glass platform can be

utilized as sensitive temperature sensors. The measurement of the 3C-SiC-on-glass-based temperature sensors was conducted in an oven with precisely controlled temperature of $\pm 0.1^\circ\text{C}$. The resistance change of the SiC sensor was measured against temperature in the range from room temperature to 473 K. The temperature was increased by 20°C per step and the resistance of SiC was recorded using a digital multimeter (i.e., Agilent B1500). **Figure 3** shows that the resistance of the SiC sensor significantly increases with increasing temperature within the testing range. It should be pointed out that the increment in

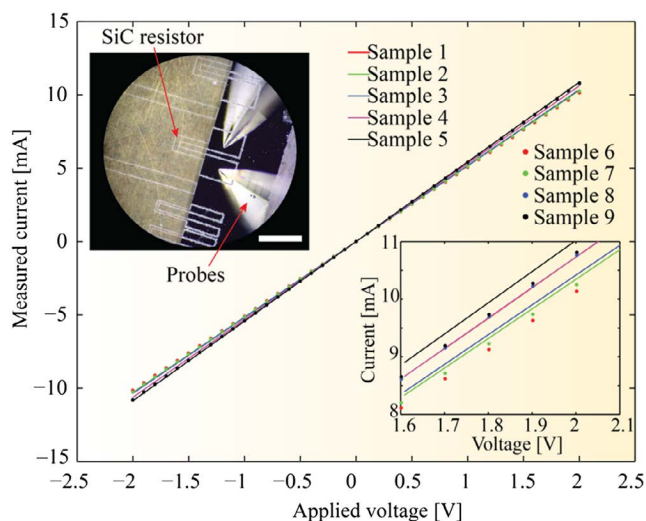


Figure 2. Current–voltage (I – V) characteristics of the fabricated SiC resistors at room temperature ($\approx 18^\circ\text{C}$). The test was conducted with nine samples for which the I – V characteristics are almost identical for all tested SiC resistors. The data indicate the uniformity and consistency of the laser ablation in patterning SiC structures. Inset: Top-left: Microscopic photograph of U-shaped SiC structures on the transparent glass substrate (dark-color regions are metal contacts), scale bar, 1000 μm . Bottom-right: Zoom-in view of the I – V curve at voltage from 1.6 to 2.1 V.

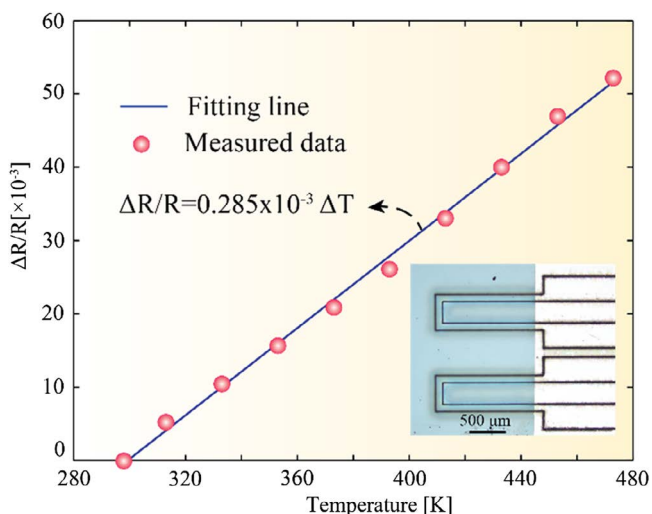


Figure 3. Characterization of 3C-SiC-on-glass temperature sensors: the resistance variation is in a linear regression with the increasing temperature from 293 to 473 K, indicating the merit of the as-fabricated SiC structures for temperature sensing. Inset: Microscopic photograph of SiC temperature sensors.

the resistance of the SiC indicates that the decrease in electron mobility is more dominant than the increase in thermally activated carrier concentration that reduces the resistance. The reduction of the electron mobility at elevated temperatures is due to electron–electron and electron–phonon scattering, which are more dominant in highly doped semiconductors. The thermal resistive effect in SiC films can be quantified by the

temperature coefficient of resistance, $\text{TCR} = \frac{\Delta R}{R \Delta T}$. Accordingly, the TCR in the highly doped 3C-SiC-on-glass was found to be 285 ppm K^{-1} .

3.2. Microheaters

Microheaters can be used as the heat source of mass-flow sensors or to provide thermal stimuli to biospecies grown on SiC, due to the good biocompatibility of SiC.^[16–18] As the glass substrate is an excellent electrical insulator, the use of 3C-SiC-on-glass heaters will confine heating power on the SiC resistors, locally raising temperatures at the targeted areas due to the Joule heating effect. We applied a voltage to a spring-shaped SiC microheater and observed its temperature change using an infrared (IR) microscope to demonstrate the function of 3C-SiC-on-glass heaters. Prior to applying the voltage to the SiC resistors, the surface of SiC was coated with a carbon powder layer with a known emissivity which was calibrated by varying the surface temperature of this coating layer using a hot plate. This calibrated emissivity (ranging from 0.92 to 0.98) was used to derive the actual temperature generated from the SiC heaters under applied DC voltages. **Figure 4** shows the temperature of the SiC heater at 0, 3, 6, and 9 V, for which the temperature of the heater can reach above 100°C under an applied power of 0.15 W. The measured temperature distribution is in good agreement with a finite element analysis (FEA) with a conductivity of SiC of $1.25 \times 10^5 \text{ S m}^{-1}$ (**Figure 4b**). In the FEA model, the SiC layer with a thickness of 600 nm on top of 1 mm thick glass substrate was simulated. The basic mechanical, electrical, and thermal properties of the glass layer were derived from integrated parameters within the software (i.e., COMSOL Multiphysics) (also available elsewhere). The Young's modulus and thermal conductivity of SiC are set as 350 GPa and $350 \text{ W m}^{-1} \text{ K}^{-1}$, respectively; the electrical conductivity of SiC is calculated from its resistivity: $\sigma = 1/\rho = 1.25 \times 10^5 \text{ S m}^{-1}$. The measured temperature of the glass substrate at the vicinity of the SiC heater was slightly higher than the simulation result, which is attributed to an increase in the thermal conductance caused by the carbon coating layer.

Figure 4c shows the relationship between the maximum temperature generated using the spring-shaped SiC microheater versus the applied electric power. The heater can generate a high temperature with a relatively small supplied power. This is due to the nearly zero leakage current from SiC to the glass substrate, in which the electrical current only flows in the SiC heater. Therefore, the integrated SiC heater at a relatively low voltage/power shows a promising feature for biocell thermal stimulation applications (e.g., cell lysis), which also takes advantage of the robustness of SiC with respect to chemical or biological environment.

3.3. Microforce Sensors

To characterize the SiC-based force sensors, mesa SiC resistors on a 3C-SiC-on-glass beam were formed in a U-shape with a longitudinal edge (parallel to the beam's length) much larger than the transverse one (perpendicular to the beam's length) (**Figure 5**). The fabricated SiC structures can be used as a force sensitive sensor owing to the large piezoresistance of SiC.^[19,20]

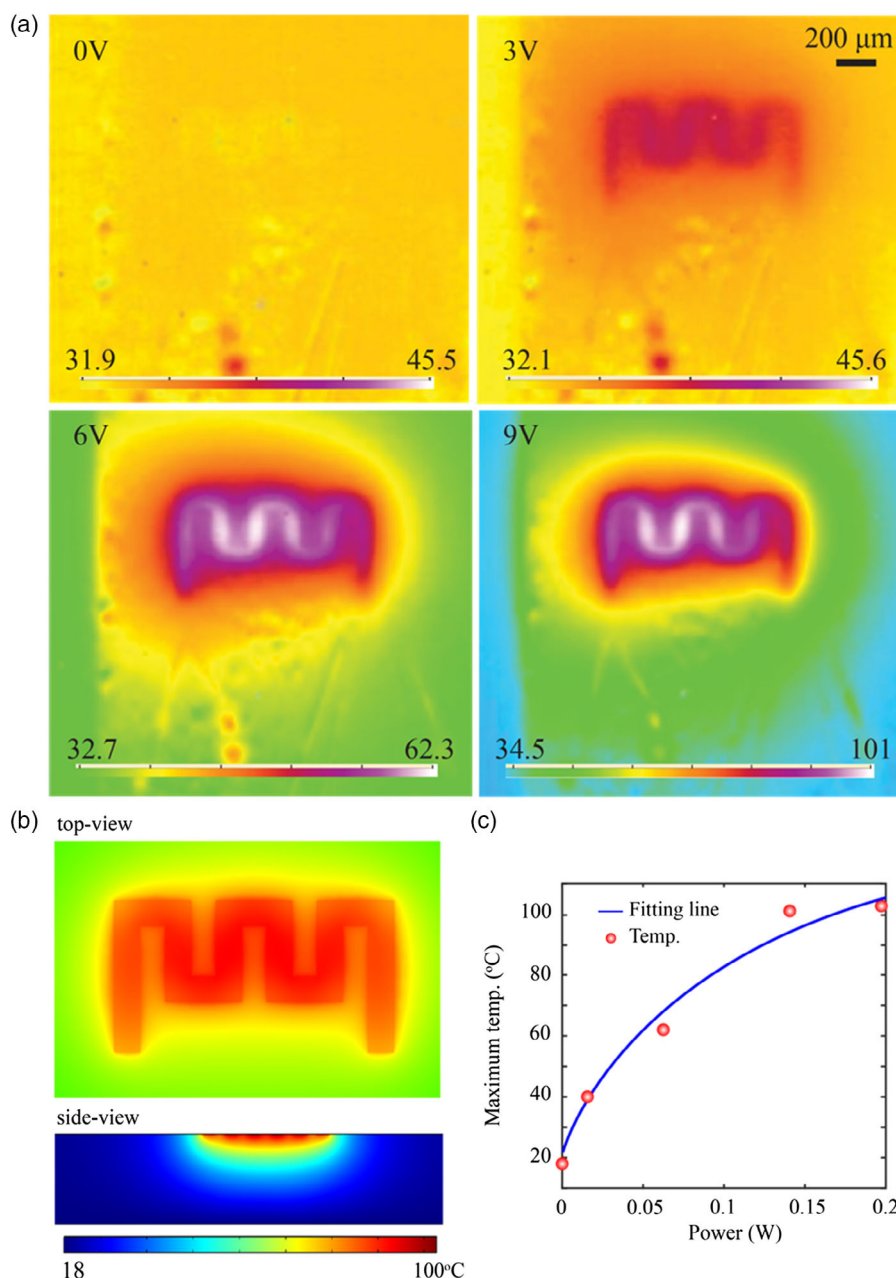


Figure 4. Demonstration of spring-shaped SiC microheater employing Joule heating effect (unit of the temperature scale bar: °C): a) Thermal image of the sensor under an applied voltage of 0, 3, 6, and 9 V using an IR camera (QFI InfraScope II) at an ambient temperature of 18 °C. b) FEA of SiC heater on glass substrate at an applied voltage of 9 V. c) Relationship between maximum generated temperature on the heater versus supplied power.

The bending beam method was used to measure a targeted force if it is applied to a free end of the beam and induces uniaxial strain in the SiC resistors located on the beam-shaped chips (length, width, and thickness are 15 mm × 2 mm × 0.5 mm). The SiC piezoresistors are located at the vicinity of the other end of the cantilever, which is clamped, to yield the highest possible induced strain.

Figure 5a shows the variation of the output electrical current with respect to an applied force of 320 mN (at a supplied voltage

of 0.1 V). At the force application state, the electrical current flowing through the SiC sensor significantly increased and remained stable throughout the duration of the applied force. This indicates that the resistance of the SiC sensor decreases with the applied strain, showing a negative gauge factor ($GF = \frac{\Delta R/R}{\epsilon}$). As the applied strain can be derived by the previous study,^[21] $\epsilon = \frac{6FL}{EbL^2}$, where F is the applied force; L , b , and t are the length, width, and thickness of the beam; and E is the Young's modulus of glass, $E = 75$ GPa. Consequently, the GF of the

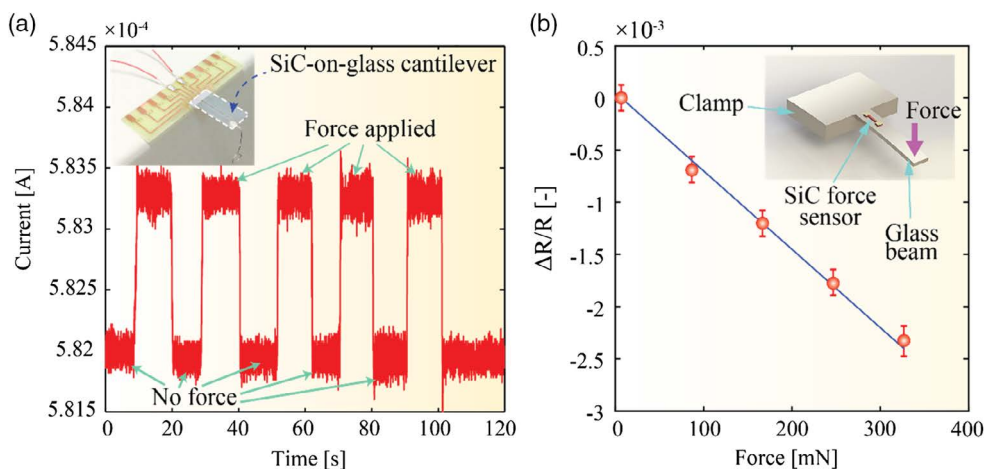


Figure 5. Demonstration of SiC force sensors. a) The change of electric current under a constant applied force ($F = 320$ mN). Inset: Bending beam method was used to measure applied forces. b) Resistance change of SiC force sensor under incremental forces (80 mN per step). Inset: Sketch of SiC force sensor test.

n-type SiC was found to be -10.3 , which is equivalent to the GFs of other SiC strain sensors fabricated using conventional lithography processes.^[22,23] If the force was completely removed, the electrical current instantaneously returned back to its original value without any drift or hysteresis under tens of applied cycles. This characteristic shows the good repeatability and fast response of the SiC force sensor.

To confirm the linearity of the SiC force sensor, a stepped loading from 0 to 320 mN with an interval of 80 mN was then applied. Figure 5b clearly shows that the linear change in the current with the applied force exhibited the excellent linearity of the sensor in measuring force and strain. The good linearity and repeatability of the SiC force sensor demonstrate the potential of our simple fabrication technique in the development of SiC-based mechanical sensors.

4. Conclusion

We demonstrate a single-step and cost-effective fabrication technique to form SiC microstructures on an insulating substrate for a MEMS-based multifunctional platform consisting of microscale sensors and heaters utilizing direct laser ablation. This method eliminates the requirement for sophisticated lithography and etching processes in a cleanroom facility, reducing the cost associated with micromachining fabrications as well as allowing fast prototyping of SiC-based structures for MEMS applications. As a proof of concept, we designed and tested multifunctional SiC-based microheaters, temperature, and force sensors on a single chip. The developed miniaturized sensors exhibited high sensitivity and good repeatability/linearity, while the integrated heater can effectively generate a temperature of up to 100°C with a relatively low power. This 3C-SiC based multifunctional platform is promising for a wide range of sensing and heating applications at the micro-scale utilizing the fast prototyping capability of direct UV laser ablation.

Acknowledgements

T.-K.N. and H.-P.P. contributed equally to this work. This work was supported by Foundation for Australia–Japan Studies (FAJS) grant. The fabrication and characterization were performed at the Queensland node of the Australian National Fabrication Facility (ANFF), a company established under the National Collaborative Research Infrastructure Strategy to provide nano- and microfabrication facilities for Australia's researchers. N.-T.N. and D.V.D. acknowledge funding support from the Australian Research Council grants LP160101553, LP150100153, and LE190100066.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

force sensors, laser ablation, microheater, silicon carbide, temperature sensors

Received: September 28, 2019

Revised: January 10, 2020

Published online: February 6, 2020

- [1] C.-M. Zetterling, *MRS Bull.* **2015**, *40*, 431.
- [2] X. Lu, J. Y. Lee, Q. Lin, *Sci. Rep.* **2015**, *5*, 17005.
- [3] H.-P. Phan, T.-K. Nguyen, T. Dinh, A. Iacopi, L. Hold, M. J. A. Shiddiky, D. V. Dao, N.-T. Nguyen, *Adv. Eng. Mater.* **2018**, *20*, 1700858.
- [4] X. L. Feng, M. H. Matheny, C. A. Zorman, M. Mehregany, M. L. Roukes, *Nano Lett.* **2010**, *10*, 2891.
- [5] H.-P. Phan, K. M. Dowling, T. K. Nguyen, T. Dinh, D. G. Senesky, T. Namazu, D. V. Dao, N.-T. Nguyen, *Mater. Des.* **2018**, *156*, 16.
- [6] D. G. Senesky, B. Jamshidi, C. Kan Bun, A. P. Pisano, *IEEE Sens. J.* **2009**, *9*, 1472.
- [7] T. Lehmann, J. Baier, A. Leineweber, A. Kienzle, J. Bill, *Adv. Eng. Mater.* **2015**, *17*, 1631.

- [8] M. A. Lantz, B. Gotsmann, P. Jaroenapibal, T. D. B. Jacobs, S. D. O'Connor, K. Sridharan, R. W. Carpick, *Adv. Funct. Mater.* **2012**, 22, 1639.
- [9] T.-K. Nguyen, H.-P. Phan, T. Dinh, K. M. Dowling, A. R. M. Faisal, D. G. Senesky, N.-T. Nguyen, D. V. Dao, *Mater. Des.* **2018**, 156, 441.
- [10] L. Wang, S. Dimitrijevic, J. Han, P. Tanner, A. Iacopi, L. Hold, *J. Cryst. Growth* **2011**, 329, 67.
- [11] H. P. Phan, H. H. Cheng, T. Dinh, B. Wood, T. K. Nguyen, F. Mu, H. Kamble, R. Vadivelu, G. Walker, L. Hold, A. Iacopi, B. Haylock, D. V. Dao, M. Lobino, T. Suga, N. T. Nguyen, *ACS Appl. Mater. Interfaces* **2017**, 9, 27365.
- [12] C. Tudryn, S. Schweizer, R. Hopkins, L. Hobbs, A. J. Garratt-Reed, *J. Electrochem. Soc.* **2005**, 152, E131.
- [13] J.-H. Lee, I. Bargatin, J. Park, K. M. Milaninia, L. S. Theogarajan, R. Sinclair, R. T. Howe, *J. Vac. Sci. Technol. B* **2012**, 30, 042001.
- [14] C. A. Zorman, R. J. Parro, *Phys. Status Solidi B* **2008**, 245, 1404.
- [15] A. R. Md Faisal, A. Qamar, H. P. Phan, T. Dinh, K. N. Tuan, P. Tanner, E. W. Streed, D. V. Dao, *ACS Appl. Mater. Interfaces* **2017**, 9, 39921.
- [16] V. Naglieri, B. Gludovatz, A. P. Tomsia, R. O. Ritchie, *Acta Mater.* **2015**, 98, 141.
- [17] S. J. Schoell, M. Sachsenhauser, A. Oliveros, J. Howgate, M. Stutzmann, M. S. Brandt, C. L. Frewin, S. E. Saddow, I. D. Sharp, *ACS Appl. Mater. Interfaces* **2013**, 5, 1393.
- [18] J. Fan, H. Li, J. Jiang, L. K. So, Y. W. Lam, P. K. Chu, *Small* **2008**, 4, 1058.
- [19] J. Bi, G. Wei, L. Wang, F. Gao, J. Zheng, B. Tang, W. Yang, *J. Mater. Chem. C* **2013**, 1, 4514.
- [20] X. Li, S. Chen, P. Ying, F. Gao, Q. Liu, M. Shang, W. Yang, *J. Mater. Chem. C* **2016**, 4, 6466.
- [21] H.-P. Phan, T. Dinh, T. Kozeki, T.-K. Nguyen, A. Qamar, T. Namazu, N.-T. Nguyen, D. V. Dao, *IEEE Electron Device Lett.* **2016**, 37, 1029.
- [22] H.-P. Phan, T.-K. Nguyen, T. Dinh, H.-H. Cheng, F. Mu, A. Iacopi, L. Hold, D. V. Dao, T. Suga, D. G. Senesky, N.-T. Nguyen, *Phys. Status Solidi A* **2018**, 215, 1800288.
- [23] T. Akiyama, D. Briand, N. F. de Rooij, *J. Micromech. Microeng.* **2012**, 22, 085034.