Materials and Design 156 (2018) 441–445

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Highly sensitive 4H-SiC pressure sensor at cryogenic and elevated temperatures

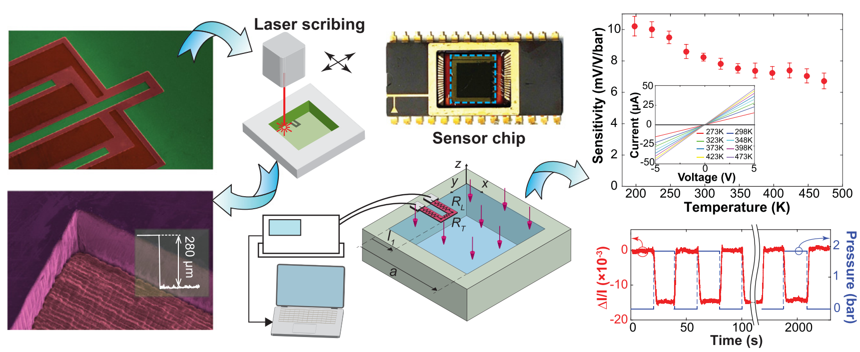
Tuan-Khoa Nguyen[a,*], Hoang-Phuong Phan[a], Toan Dinh[a], Karen M. Dowling[b], Abu Riduan Md Foisal[a], Debbie G. Senesky[c], Nam-Trung Nguyen[a], Dzung Viet Dao[a,d]

[a] *Queensland Micro-Nanotechnology Centre, Griffith University, Brisbane, Australia*
[b] *Department of Electrical Engineering, Stanford University, USA*
[c] *Department of Aeronautics and Astronautics, Stanford University, USA*
[d] *School of Engineering and Built Environment, Griffith University, Gold Coast, Australia*

HIGHLIGHTS

- A highly sensitive bulk silicon carbide pressure sensor was fabricated using a laser scribing method.
- The sensor's sensitivity was obtained to be 10.83 mV/V/bar at 198 K and 6.72 mV/V/bar at 473 K.
- The sensor shows a two-fold increment of sensitivity in comparison with other silicon carbide pressure sensors.
- The as-fabricated sensor exhibits excellent sensitivity, linearity and reproducibility from cryogenic to elevated temperatures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 May 2018
Received in revised form 30 June 2018
Accepted 6 July 2018
Available online 10 July 2018

Keywords:
Piezoresistive
Pressure sensor
Silicon carbide

ABSTRACT

The slow etching rate of conventional micro-machining processes is hindering the use of bulk silicon carbide materials in pressure sensing. This paper presents a 4H-SiC piezoresistive pressure sensor utilising a laser scribing approach for fast prototyping a bulk SiC pressure sensor. The sensor is able to operate at a temperature range from cryogenic to elevated temperatures with an excellent linearity and repeatability with a pressure of up to 270 kPa. The good optical transparency of SiC material allows the direct alignment between the pre-fabricated piezoresistors and the scribing process to form a diaphragm from the back side. The sensitivities of the sensor were obtained as 10.83 mV/V/bar at 198 K and 6.72 mV/V/bar at 473 K, which are at least a two-fold increment in comparison with other SiC pressure sensors. The high sensitivity and good reliability at either cryogenic and elevated temperatures are attributed to the profound piezoresistive effect in p-type 4H-SiC and the robust p-n junction which prevents the current from leaking to the substrate. This indicates the potential of utilising the laser scribing approach to fabricate highly sensitive bulk SiC pressure sensors for harsh environment applications.

1. Introduction

Micromachined-pressure sensors are positioned as the most important and ubiquitous micro-electromechanical systems (MEMS) sensing devices. In terms of the sensing mechanism, capacitive and piezoresistive transducers play a dominant role with the simple read-out, good reliability and integration [1–3]. Piezoresistive sensors possessed several advantages in comparison with capacitive counterparts such as the easiness of design configuration and the wider linearity range [4–7]. In the past four decades, Si remains as the most important material used for pressure sensors owing to its

* Corresponding author.
E-mail address: khoa.nguyentuan@griffithuni.edu.au (T.-K. Nguyen).

https://doi.org/10.1016/j.matdes.2018.07.014

wide availability and mature fabrication process. However, its intrinsic physical properties, such as the low energy band gap and plastic deformation, have limited its usage in harsh environments. In contrast, the superior mechanical strength, excellent corrosive/shock resistance and high stability at high temperatures position silicon carbide a promising material for extreme condition sensing. In fact, numerous SiC pressure sensors have been reported including capacitive and piezoresistive sensors [8–10]. For instance, Young et al. characterized a 3C-SiC⟨100⟩ capacitive pressure sensor with a sensitivity of 7.7 fF/torr at 400 °C [11]. Wu et al. reported a SiC-on-SiO_2 piezoresistive pressure sensor with sensitivity of 101.5 μ V/V/psi at room temperature and 53.4 μ V/V/psi at 385 °C [12,13]. Wieczorek et al. reported a 6H-SiC pressure sensor with a sensitivity of 330 μ V/V/bar at 23 °C and 200 μ V/V/bar at 400 °C [14]. Okojie et al. found a sensitivity recovery at high temperatures of a 4H-SiC pressure sensor with good linearity [15].

The use of bulk SiC materials (e.g. 4H-SiC and 6H-SiC) for pressure sensors can eliminate the thermal expansion mismatch between the sensing layer and supporting diaphragm and extend the working regime of the sensing devices. Moreover, the high energy band gap of 4H-SiC (i.e. 3.23 eV) significantly reduces the number of thermal activated electron-hole pairs, improving the reliability and stability of 4H-SiC based sensors in extreme conditions [16,17]. However, the high resistance to chemical substances of bulk SiC polytypes makes the etching very challenging and expensive. For instance, the only technique to chemically etch SiC is to use molten salt fluxes and hot gases with an electrochemical processing [18]. These corrosive media typically require expensive Pt beakers and masks to withstand those molten solutions. Moreover, the plasma etching of SiC results in a very slow etch rate, making it impractical to form a diaphragm for the pressure sensors from bulk SiC wafers. To overcome the challenge, Akiyama et al. employed a mechanical drilling process to etch bulk SiC material forming a 4H-SiC pressure sensor [19]. This method requires specified wafer holders and alignment tools that significantly increase the preparation time and fabrication cost.

In this paper, we present a laser scribing approach to fabricate a highly sensitive 4H-SiC piezoresistive pressure sensor from a bulk SiC wafer. The good optical transparency of SiC material allows the direct alignment between the pre-fabricated piezoresistors and the laser-scribed diaphragm on the back side. Furthermore, the experimental result shows that the sensor exhibits good performance from a cryogenic temperature of 198 K to a high temperature of 473 K. A sensitivity of 8.24 mV/V/bar was achieved at room temperature, slightly increased to 10.83 mV/V/bar at 198 K and decreased to 6.72 mV/V/bar at 473 K. The high sensitivity at cryogenic and elevated temperature is attributed to the profound piezoresistive effect in p-type 4H-SiC and the robust p-n junction which effectively prevent the current from leaking to the substrate. Moreover, the good reproducibility for hundreds of pressurising cycles and excellent stability at cryogenic and high temperatures were also realized.

2. Design and fabrication of 4H-SiC pressure sensor

2.1. Pressure sensor design

In terms of design, circular and rectangular diaphragms are the two common geometries for micromachined pressure sensors. The sensing element is typically placed in the vicinity of the edge of the diaphragm to obtain the maximum sensitivity since the induced stress/strain is maximised at the given area. While the stress/strain is equally distributed along the circumference of a circular diaphragm, in a rectangular diaphragm, it is concentrated in the middle of the edges. From the plate theory, the maximum stress/strain of the square diaphragm is 1.64 times higher than that of a circular diaphragm with equivalent dimensions [20]. Thus, placing the sensing element in the middle of the edges of a rectangular diaphragm would yield the maximum sensitivity for the pressure monitoring. Therefore, in this paper, a square-shaped diaphragm was designed and fabricated with piezoresistors located in the middle of an edge, as illustrated in Fig. 1. An applied differential pressure would deform the diaphragm and induce strain to the piezoresistor lying on the top surface of the diaphragm. Since the sensor is made of 4H-SiC, a piezoresistive material, the magnitude of applied strain can be realized by monitoring the resistance change of the sensor. Moreover, by establishing a straining model, it is possible to detect the input pressure applied to the diaphragm. The stress/strain distribution of a square diaphragm under pressure can be characterized using the Bubnov-Galerkin model for a rectangular thin film based on the maximum deflection of the diaphragm under pressure. The simplified function for the strain distribution along the centre line ($x = (-a/2, a/2), y = 0$) of a square diaphragm is deduced as [21]

$$f(x) = \frac{7P}{2304a^4D}\left(x^2 - \frac{a^2}{4}\right)^2 \tag{1}$$

where $f(x), P$ and a are the deflection function, the edge length of the square diaphragm, and the applied pressure, respectively; $D = Et^3/(12(1-\nu))$ is the flexural rigidity of the diaphragm; t is the diaphragm thickness; ν and E are the Poisson's ratio and Young's modulus of 4H-SiC, respectively. It is worth noting that when the diaphragm deflection is much smaller than the thickness ($f \ll t$), the relationship between f and P is linear.

The strain function with respect to the small deflection of a square diaphragm can be given as

$$\varepsilon(x) = z\frac{\partial^2 f}{\partial x^2} \tag{2}$$

where z denotes the dimension that is perpendicular to the diaphragm plane. The U-shaped piezoresistor consists of two long resistors R_l and one short resistor R_t. Upon an applied pressure, R_l varies by longitudinal gauge factor (G_l) while the R_t change according to transverse gauge factor (G_t), and either G_l and G_t were reported in our previous work [22]. Thus, the fractional change of resistance of the combined piezoresistor can be given as

$$\frac{\Delta R}{R} = \int_0^{l_1} \bar{r}_l G_l \varepsilon(x)dx + \bar{r}_t G_t \varepsilon_t \tag{3}$$

where $\varepsilon(x)$ is the function of the localised strain (see supplementary document for the detailed calculation) and ε_t is the strain at the location of R_l, $\bar{r}_l = 2R_l/R$ and $\bar{r}_l = R_t/R$ are the ratio of the longitudinal

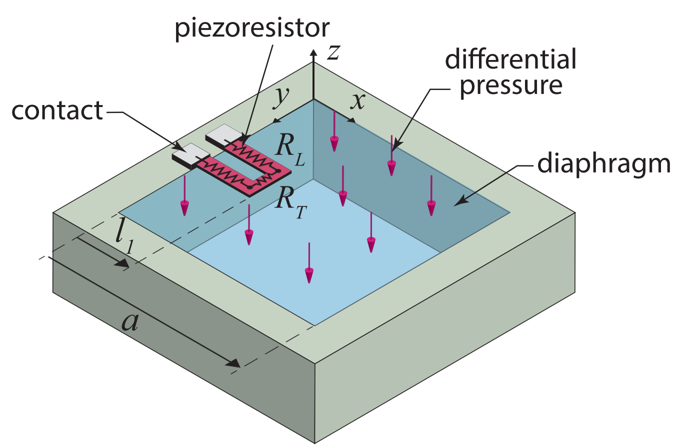


Fig. 1. Design and configuration of 4H-SiC pressure sensor.

and transverse resistances. Thus, the sensitivity of the sensor can be given as

$$S = \left|\frac{\Delta R/R}{P}\right| = \left|\frac{\Delta I/I}{P}\right|. \quad (4)$$

The detailed sensitivity analysis can be found in the supplementary document.

2.2. Fabrication

Fig. 2(a) shows the fabrication process of the 4H-SiC pressure sensor. The initial 4H-SiC wafer consists of 1 μ m p-type, 1 μ m n-type layers and a 350 μ m low doped substrate. The sensor was fabricated from p-type 4H-SiC in the s-face (i.e. (0001) face). The U-shaped piezoresistors were patterned on the p-type layer by a photo lithography (step ①) and inductive coupled plasma (ICP) etching (step ②) using a STS™ etcher at an etch depth of 1.25 μ m, ensuring that the p-type functioning layer was thoroughly etched and the piezoresistors electrically isolated from the substrate (Fig. 2(b)). The ICP etching rate was approximately 100 nm/min. Next, Ti/Al metallization (step ③) was patterned on top of the p-type layer, following a rapid thermal annealing process (RTP) at 1000 °C to obtain a good Ohmic contact for the sensor's characterization. It is known that p-type 4H-SiC is a wide band gap material with a different work function from that of the metal contact (i.e. Ti/Al), a potential barrier is formed after the metallization process [23]. This leads to the a Schottky contact, in which the current-voltage characteristics shows a rectifying behaviour when sweeping a voltage range from negative to positive. The sheet contact resistances before and after the annealing process at were measured to be 2.1 MΩ/□ and 26.7 kΩ/□, respectively. This means that the thermal annealing has greatly improved the Ohmic behaviour of the contact between p-type 4H-SiC and Ti/Al. The wafer was subsequently diced in to 10 × 10 mm^2 chips. Finally, the square-shaped diaphragms were formed by scribing the back side of each chip (step ④) by a diode-pumped Nd/YVO_4 laser with a peak power of up to 1.5 kW and the average scribing power was 1–3 W (Fig. 2(c), (d)). The details of laser scribing process can be found elsewhere [24]. First, the 4H-SiC sample (with the pre-fabricated piezoresistor) was placed in the chamber to align the laser focus. Subsequently, the scribing process was conducted on the back of the 4H-SiC chip (engraving on the side without the piezoresistor). The material was ablated layer-by-layer using the laser beam with the cross-hatch patterning until the desired depth is achieved. The total time for the laser scribing procedure was just approximately 25 min. The scribing time is far less than that of other etching processes for bulk SiC materials (e.g. inductive plasma etching, deep reactive-ion etching (DRIE)) which could take many hours or even impractical to conduct for the etch depth of hundreds of micrometres. It should be noted that owing to the transparency of the SiC wafer, the alignment of back side scribing to the pre-fabricated piezoresistor in the front side was made straightforward. Fig. 2(c) shows the side-wall and surface roughness of the back side of the diaphragm after the laser scribing process. The final dimensions and thickness of the diaphragms were measured to be 5 × 5 mm^2 and 70 μm, respectively. After the fabrication process, the chips were attached to ceramic chip carriers which are aimed to work at cryogenic and high temperatures, as shown in Fig. 2(e). The electrical connections were formed by wire bonding from the Ti/Al contact to the contact pads of the chip carrier. The enclosed cavity underneath the 4H-SiC diaphragm was sealed by high-temperature epoxy.

3. Results and discussion

Fig. 2(f) shows the experimental setup for the characterization of the 4H-SiC pressure sensor. The 4H-SiC chip attached to a chip carrier was placed in the chamber of a Linkam™ THMS600. First, the sensor operation at room temperature was characterized. The measurement started with supplying controlled air pressure to the enclosed chamber using a pressure regulator. In order to avoid oxidation at elevated temperature, argon was supplied as the medium in the pressurizing chamber. A constant DC voltage of 1 V was applied to the piezoresistor in the measurement. Subsequently, the output current was monitored by an external read-out device (Agilent™ 1500).

Fig. 3(a) shows the recorded real-time output signal which varied linearly with the increase of the applied pressure from 0 to 268 kPa. Moreover, an increasing resistance with applied pressure can also be observed in Fig. 3(b), indicating that the piezoresistor is in the tensile stress state (the resistance increases with strain). The measured data shows the good linearity of the output signal and the input pressure with high signal-to-noise ratio. It should be noted that when

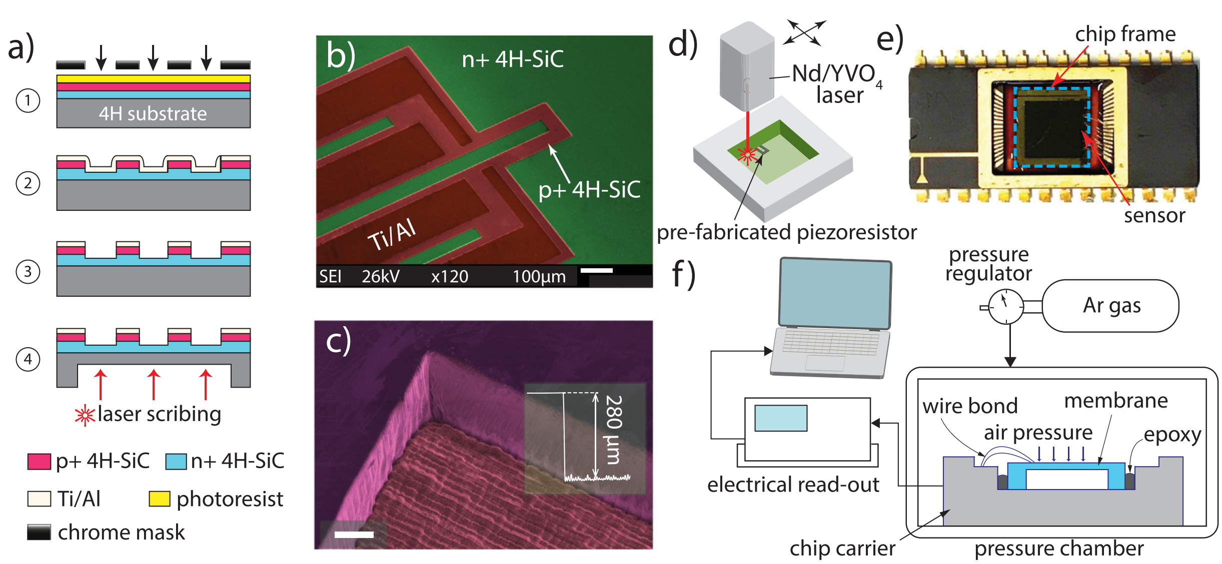


Fig. 2. a) Fabrication process of 4H-SiC pressure sensor. b) SEM image of the sensor on the top surface of a diced chip. c) SEM image of the back side of the diaphragm after laser scribing. Scale bar, 100 μm. d) Alignment of laser scribing on the back side with respect to the pre-fabricated sensor on the front side. e) Sensor chip attached to a chip carrier with bonding wire. f) Experimental setup for the pressurising characterization.

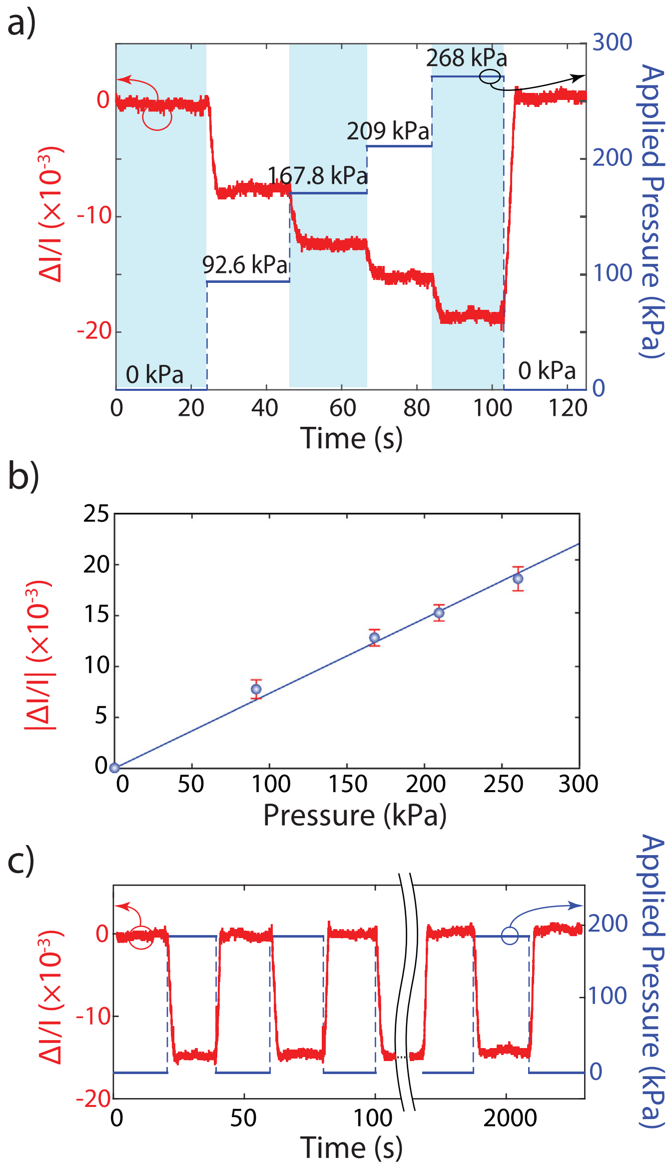


Fig. 3. a) Real-time measurement of output signal at varying applied pressure ranging from 0 to nearly 270 kPa. b) Linear resistance change upon the application of pressure. c) Output signal at a cyclic applied pressure of 186 kPa, high signal-to-noise ratio and the excellent reproducibility without significant signal drift were obtained.

the differential pressure was completely removed, the output signal returned to its initial value without any drift. Another measurement with a cyclic pressure of 186 kPa was also performed, confirming the excellent repeatability of the sensor with cyclic pressure, as shown in Fig. 3(c). The experimental data exhibits the good reproducibility and linearity of the output signal which is crucial for pressure sensing which typically requires long-term stability. It is also necessary to determine the time response of the pressure sensor. From a finite element analysis (FEA) using COMSOL™, the first order resonant frequency of the membrane f_1 was found to be 108 kHz, corresponding to the response in the time domain of 9.2 μs. This value is equivalent to the time response of other reported SiC pressure sensors.

To demonstrate the capability of the as-fabricated sensor for harsh environments, the operation of the sensor at cryogenic and elevated temperatures were characterized. It is known that many pressure sensors exhibit good performances at room temperature but at high temperatures, there is a significant reduction in the sensitivity and reliability due to the thermal induced leakage current to the substrate. Therefore, the current-voltage characteristics at a temperature range from 273 K to 473 K was measured as shown in Fig. 4 Inset. It should be noted that the leakage is four orders of magnitude smaller than the current flowing in the p-type piezoresistors thanks to the robust p-n junction. This barrier layer acts as a back-to-back diode which prevents the electric current leaking to the substrate at the high temperatures [22,25]. Consequently, it can be concluded that only the p-type layer contributed to the measurement of the piezoresistive pressure sensor.

Fig. 4 shows the measured sensitivity of the 4H-SiC pressure sensor at a temperature range from 198 K to 473 K. A sensitivity of 10.83 mV/V/bar was realized at 198 K then gradually decreased to 6.72 mV/V/bar at 473 K. This decrease in sensitivity by temperature can be explained by the strain induced effect of the electrical conductance of p-type semiconductor materials with respect to the temperature variation. The electrical conductivity in p-type 4H-SiC is mainly attributed to the hole transfer in the three top highest valence bands (i.e. the heavy hole (HH), light hole (LH), and spin-orbit split-off (SOSO) bands). Since 4H-SiC is an α-type SiC in which spin-orbit interaction has weak effect on the shape of the valence bands [26], the electrical conductance can be deduced as [27,28]

$$\sigma_{4HSiC} = q^2\tau\left(\frac{p_1}{m_1} + \frac{p_2}{m_2}\right) \tag{5}$$

where q, τ, p_i and m_i are the electron charge, the relaxation time, the hole concentration ($i = 1$ denotes the HH band and $i = 2$ represents the LH band), and the effective mass, respectively. The application of a uniaxial stress lifts the degeneracy of the HH and LH bands, altering the resistivity of the piezoresistor. This phenomenon is attributed to the hole transfer mechanism which is the dominant factor of the piezoresistivity in p-type semiconductors. Subsequently, in the small strain region ($\Delta E_V \ll 2k_BT$) the relative variation of the hole concentration in the HH and LH band is given as [27]

$$\frac{\Delta R}{R} = -\frac{\Delta p_i}{p_i} = -\frac{1}{k_BT}\frac{\Delta E_V}{1+\left(m_i^*/m_j^*\right)^{3/2}} \tag{6}$$

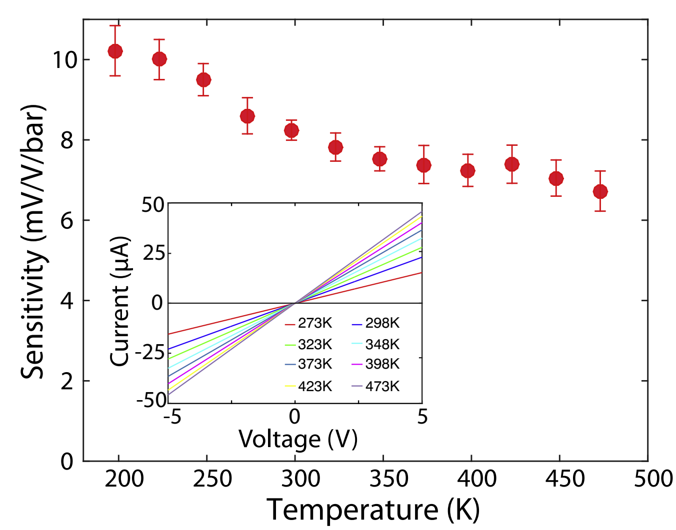


Fig. 4. The measured sensitivity at various temperature ranging from 198 K to 473 K. It is worth noting that the decreasing of sensitivity with increasing temperature is in good agreement with the hole transfer mechanism under strain with the varying temperature. Inset: Linear current-voltage characteristics of the sensor measured at various temperatures.

where m_i^* are the density-of-states effective masses, p_i are the hole concentration, ΔE_V is the band splitting energy and k_B is the Boltzmann constant. Assuming that the component $\Delta E_V / \left(1 + \left(m_i^*/m_j^*\right)^{3/2}\right)$ is independent on temperature change, the relative resistance change or the sensitivity is inversely proportional to the increase of the ambient temperature. Therefore, the measured sensitivity of the 4H-SiC in the given temperature range is in good agreement with the aforementioned variation with temperature of the hole transfer mechanism in p-type 4H-SiC.

4. Conclusion

In summary, we present the fabrication and characterization of a highly sensitive 4H-SiC pressure sensor using a laser scribing approach. The sensor was aimed to work in a wide range of temperature from 198 K to 473 K with high sensitivities of 10.83 mV/V/bar at 198 K and 6.72 mV/V/bar at 473 K. These results exhibited a two-fold sensitivity increase in comparison with other reported SiC pressure sensors with the excellent linearity and repeatability. The variation of the sensor's piezoresistivity with temperature can be explained by the hole transfer mechanism between the light hole and heavy hole bands of p-type 4H-SiC. The high sensitivity and good reliability at either cryogenic and elevated temperatures were achieved thanks to the profound piezoresistive effect of p-type 4H-SiC material and the robust p-n junction which prevents the current from leaking to the substrate at either cryogenic and high temperatures. The good Ohmic contact was formed using a rapid thermal annealing at 1000 °C, which is then confirmed by the linear current-voltage characteristic at the temperature range. This temperature-tolerance Ohmic characteristic is favourable for the piezoresistive sensing in terms of sensitivity and reliability. The as-presented laser scribing approach shows the feasibility of fast prototyping bulk SiC pressure sensors for harsh environment sensing.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Acknowledgments

This work has been partially supported by Australian Research Council (ARC), Australia grants LP150100153 and LP160101553. This work was performed in part at the Queensland node of the Australian National Fabrication Facility (ANFF), Australia, a company established under the National Collaborative Research Infrastructure Strategy to provide nano- and micro-fabrication facilities for Australian researchers. T.-K. Nguyen acknowledges Postgraduate Research Scholarship (GUPRS) and International Postgraduate Research Scholarship (GUIPRS) from Griffith University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2018.07.014.

References

[1] Y. Liu, H. Zheng, M. Liu, High performance strain sensors based on chitosan/carbon black composite sponges, Mater. Des. 141 (2018) 276–285. https://doi.org/10.1016/j.matdes.2017.12.046.

[2] H. Souri, D. Bhattacharyya, Wearable strain sensors based on electrically conductive natural fiber yarns, Mater. Des. 154 (2018) 217–227. https://doi.org/10.1016/j.matdes.2018.05.040.

[3] J.F. Christ, N. Aliheidari, A. Ameli, P. Pötschke, 3D printed highly elastic strain sensors of multiwalled carbon nanotube/thermoplastic polyurethane nanocomposites, Mater. Des. 131 (2017) 394–401. https://doi.org/10.1016/j.matdes.2017.06.011.

[4] H. Takahashi, N.M. Dung, K. Matsumoto, I. Shimoyama, Differential pressure sensor using a piezoresistive cantilever, J. Micromech. Microeng. 22 (5) (2012) 055015. https://doi.org/10.1088/0960-1317/22/5/055015.

[5] I. Godovitsyn, V. Amelichev, V. Pankov, A high sensitivity surface-micromachined pressure sensor, Sens. Actuators A 201 (2013) 274–280. https://doi.org/10.1016/j.sna.2013.07.006.

[6] J. Wang, R. Chuai, L. Yang, Q. Dai, A surface micromachined pressure sensor based on polysilicon nanofilm piezoresistors, Sens. Actuators A 228 (2015) 75–81. https://doi.org/10.1016/j.sna.2015.03.008.

[7] T.-L. Chou, C.-H. Chu, C.-T. Lin, K.-N. Chiang, Sensitivity analysis of packaging effect of silicon-based piezoresistive pressure sensor, Sens. Actuators A 152 (1) (2009) 29–38. https://doi.org/10.1016/j.sna.2009.03.007.

[8] T.-K. Nguyen, H.-P. Phan, H. Kamble, R. Vadivelu, T. Dinh, A. Iacopi, G. Walker, L. Hold, N.-T. Nguyen, D.V. Dao, Superior robust ultrathin single-crystalline silicon carbide membrane as a versatile platform for biological applications, ACS Appl. Mater. Interfaces 9 (48) (2017) 41641–41647. https://doi.org/10.1021/acsami.7b15381.

[9] H.-P. Phan, K.M. Dowling, T.K. Nguyen, T. Dinh, D.G. Senesky, T. Namazu, D.V. Dao, N.-T. Nguyen, Highly sensitive pressure sensors employing 3C-SiC nanowires fabricated on a free standing structure, Mater. Des. 156 (2018) 16–21. https://doi.org/10.1016/j.matdes.2018.06.031.

[10] H.-P. Phan, T.-K. Nguyen, T. Dinh, G. Ina, A.R. Kermany, A. Qamar, J. Han, T. Namazu, R. Maeda, D.V. Dao, N.-T. Nguyen, Ultra-high strain in epitaxial silicon carbide nanostructures utilizing residual stress amplification, Appl. Phys. Lett. 110 (14) (2017) 141906. https://doi.org/10.1063/1.4979834.

[11] D. Young, J. Du, C. Zorman, W. Ko, High-temperature single-crystal 3C-SiC capacitive pressure sensor, IEEE Sens. J. 4 (4) (2004) 464–470. https://doi.org/10.1109/JSEN.2004.830301.

[12] C.-H. Wu, S. Stefanescu, H.-I. Kuo, C.A. Zorman, M. Mehregany, Fabrication and Testing of Single Crystalline 3C-SiC Piezoresistive Pressure Sensors, Transducers '01 Eurosensors XV, 2001, pp. 514–517. https://doi.org/10.1007/978-3-642-59497-7_122.

[13] M. Fragaa, H. Furlan, M. Massia, I. Oliveiraa, L. Koberstein, Fabrication and characterization of a SiC/SiO_2/Si piezoresistive pressure sensor, Procedia Eng. 5 (2010) 609–612. https://doi.org/10.1016/j.proeng.2010.09.183.

[14] G. Wieczorek, B. Schellin, E. Obermeier, G. Fagnani, L. Drera, SiC Based Pressure Sensor for High-temperature Environments, IEEE Sensors, 2007, pp. 748–751. https://doi.org/10.1109/ICSENS.2007.4388508.

[15] R.S. Okojie, D. Lukco, V. Nguyen, E. Savrun, 4H-SiC piezoresistive pressure sensors at 800 °C with observed sensitivity recovery, IEEE Electron Device Lett. 36 (2) (2015) 174–176. https://doi.org/10.1109/LED.2014.2379262.

[16] T.-K. Nguyen, H.-P. Phan, J. Han, T. Dinh, A.R.M. Foisal, S. Dimitrijev, Y. Zhu, N.-T. Nguyen, D.V. Dao, Highly sensitive p-type 4H-SiC Van der Pauw sensor, RSC Adv. 8 (6) (2018) 3009–3013. https://doi.org/10.1039/c7ra11922d.

[17] T.-K. Nguyen, H.-P. Phan, T. Dinh, T. Toriyama, K. Nakamura, A.R.M. Foisal, N.-T. Nguyen, D.V. Dao, Isotropic piezoresistance of p-type 4H-SiC in (0001) plane, Appl. Phys. Lett. 113 (1) (2018) 012104. https://doi.org/10.1063/1.5037545.

[18] R. Cheung, Silicon Carbide Microelectromechanical Systems for Harsh Environments, Imperial College Press. 2006.

[19] T. Akiyama, D. Briand, N.F de Rooij, Piezoresistive n-type 4H-SiC pressure sensor with membrane formed by mechanical milling, IEEE Sensors, 2011, pp. 222–225. https://doi.org/10.1109/ICSENS.2011.6126936.

[20] Y. Kanda, A. Yasukawa, Optimum design considerations for silicon piezoresistive pressure sensors, Sens. Actuators A 62 (1-3) (1997) 539–542. https://doi.org/10.1016/S0924-4247(97)01545-8.

[21] E. Suhir, Structural Analysis in Microelectronic and Fiber-optic Systems, Springer. 1991. https://doi.org/10.1007/978-94-011-6535-8.

[22] T.-K. Nguyen, H.-P. Phan, T. Dinh, J. Han, S. Dimitrijev, P. Tanner, A.R.M. Foisal, Y. Zhu, N.-T. Nguyen, D.V. Dao, Experimental investigation of piezoresistive effect in p-type 4H–SiC, IEEE Electron Device Lett. 38 (7) (2017) 955–958. https://doi.org/10.1109/LED.2017.2700402.

[23] B.J. Johnson, M.A. Capano, Mechanism of ohmic behavior of Al/Ti contacts top-type 4H-SiC after annealing, J. Appl. Phys. 95 (10) (2004) 5616–5620. https://doi.org/10.1063/1.1707215.

[24] E.H. Ransom, K.M. Dowling, D. Rocca-Bejar, J.W. Palko, D.G. Senesky, High-throughput pulsed laser manufacturing etch process for complex and released structures from bulk 4H-SiC, 2017 IEEE 30th Inter. Conf. on Micro Electro Mechanical Systems (MEMS), 2017, pp. 671–674. https://doi.org/10.1109/MEMSYS.2017.7863497.

[25] T. Akiyama, D. Briand, N.F. de Rooij, Design-dependent gauge factors of highly doped n-type 4H-SiC piezoresistors, J. Micromech. Microeng. 22 (8) (2012) 085034. https://doi.org/10.1088/0960-1317/22/8/085034.

[26] C. Persson, U. Lindefelt, Relativistic band structure calculation of cubic and hexagonal SiC polytypes, J. Appl. Phys. 82 (11) (1997) 5496–5508. https://doi.org/10.1063/1.365578.

[27] P. Kleimann, B. Semmache, M.L. Berre, D. Barbier, Stress-dependent hole effective masses and piezoresistive properties of p-type monocrystalline and polycrystalline silicon, Phys. Rev. B 57 (15) (1998) 8966–8971. https://doi.org/10.1103/PhysRevB.57.8966.

[28] T. Toriyama, S. Sugiyama, Analysis of piezoresistance in p-type silicon for mechanical sensors, J. Microelectromech. Syst. 11 (5) (2002) 598–604. https://doi.org/10.1109/JMEMS.2002.802904.