Experimental Investigation of Piezoresistive Effect in p-type 4H-SiC

Tuan-Khoa Nguyen, Hoang-Phuong Phan, Toan Dinh, Jisheng Han, Sima Dimitrijev, Philip Tanner, Abu Riduan Md Foisal, Yong Zhu, Nam-Trung Nguyen and Dzung Viet Dao

Abstract—This letter presents for the first time the piezoresistive effect in p-type 4H-SiC. Longitudinal and transverse p-type 4H-SiC piezoresistors with a doping concentration of $10^{16}$ cm$^{-3}$ were fabricated along [1100] directions. Ni/Al electrodes annealed at 1000°C showed a good Ohmic contact then the longitudinal and transverse gauge factors were found to be as high as 31.5 and -27.3, respectively. The large gauge factors, attributed to the change of valence energy bands upon application of mechanical strain, and the linear relationship between the resistance change versus induced strain demonstrate the potential of p-type 4H-SiC for mechanical sensing applications.

Index Terms—4H-SiC, MEMS mechanical sensor, piezoresistive effect, silicon carbide

I. INTRODUCTION

OVER the past four decades, silicon (Si) has been one of the main materials used in MEMS sensors [1], [2]. However, Si based sensors are not suitable for a range of applications where harsh conditions, including high temperature, high pressure, strong electric fields, extremely high shock or intense vibration and aggressive chemicals exist [3], [4]. On the other hand, the superb mechanical properties of silicon carbide (SiC), along with its electrical stability at high temperatures, offer new possibilities of developing MEMS sensors for such applications [5], [6]. 4H-SiC is one of the most favorable polytypes for MEMS devices owing to its excellent properties [7] and commercial availability.

The piezoresistive effect in SiC has been extensively investigated for mechanical sensing applications [8], [9]. A cost-effective approach to develop SiC piezoresistive devices is to epitaxially grow 3C-SiC on Si wafer ($\gamma$-SiC) in which SiC would be the sensing layer, while Si acts as the substrate. This can take advantage of the wide availability and low cost of Si wafers. An early study on the piezoresistive effect in n-type 3C-SiC was conducted by Shor et al. with a negative gauge factor (GF) of -31.8 for a $10^{16}$-10$^{17}$ cm$^{-3}$ doping concentration [10]. Phan et al. reported a high GF of 30.3 in $5 \times 10^{18}$ cm$^{-3}$ doped p-type 3C-SiC [11]. Furthermore, the GFs were found to be stable at the temperature ranging from 300 to 573°C [12]. In addition, hexagonal SiC polytypes ($\alpha$-SiC), such as 4H-SiC and 6H-SiC, have attracted an increasing research interest since the use of these polytypes offers the possibility of making SiC-only devices. A GF of $3.3 \times 10^{18}$ cm$^{-3}$ doped 6H-SiC has been reported as high as -29.4, and the device could be used up to 250°C [13]. By scaling down the sizes of piezoresistors to nanometer scale, giant piezoresistances have been realized owing to the quantum confinement effect in SiC nanostructures [14], [15]. The piezoresistive effect of 4H-SiC is also of interest since this polytype can be integrated into electronic components in the same platforms. Akiyama et al. reported the piezoresistive effect in a highly doped of $1.5 \times 10^{19}$ cm$^{-3}$ n-type 4H-SiC with longitudinal and transverse GFs of -10 and 20.8, respectively [16]. A comprehensive review of the piezoresistive effect in different SiC polytypes can be found elsewhere [4].

Although the piezoresistive effect of other SiC polytypes has been reported in a large number of studies, such effect in p-type 4H-SiC, an indispensable material for MEMS and power electronics devices, has not been elucidated yet. This letter presents the first experimental investigation of the piezoresistive effect in p-type 4H-SiC with significantly large GFs. The three-point bending method was utilized to obtain the Young’s modulus of 4H-SiC, while thermally annealed Ni/Al thin film was used to form Ohmic contact for 4H-SiC piezoresistors. The experimental results shows that under uniaxial strains along [1100] orientation, the GFs of p-type 4H-SiC were found to be 31.5 and -27.3 for the longitudinal and transverse [1100] directions, respectively. The piezoresistance of p-type 4H-SiC also exhibited an excellent linearity in the induced strain range of 0 to nearly 200 με. These results indicate that p-type 4H-SiC is a promising candidate for mechanical sensors.

II. RESULTS AND DISCUSSION

The 4H-SiC wafer used in this study was purchased from Ascatron™ with a 1-μm p-type epitaxial layer grown on top of a 1-μm n-type epitaxial layer and n-type SiC substrate. A cross-sectional view of the epitaxial p-type 4H-SiC layer on n-type 4H-SiC substrate is illustrated in Fig.1 (a). The p-type layer, with aluminum dopant, and n-type layer, with nitrogen dopant, both have a carrier concentration of $10^{18}$ cm$^{-3}$. 50-nm-thick nickel and 300-nm-thick aluminum layers were deposited on the top of the p-type layer. Figure 1 (b) shows the SEM image of an array of 200 μm-long and 1000 μm-wide SiC resistors. Since 4H-SiC is a considerably wide band gap semiconductor, it is expected that after depositing metal contacts, a Schottky barrier would be formed between the p-type and metal layers. This is attributed to the large difference of the work functions of metals and wide band gap semiconductors [17]. Initially, the contact between the Ni/Al and p-type 4H-SiC layers exhibited a rectifying behavior. However, by conducting a high temperature thermal annealing
in nitrogen atmosphere, an Ohmic contact was formed in the annealed samples (Fig.1 (c)). In the annealing process, the temperature was kept at 1000°C for 2 minutes and the total duration, including heating and cooling, was approximately 1 hour. The measured sheet resistances of 1-µm p-type layer was 22.9 kΩ/□ and the contact resistance was approximately 10⁻³ Ωcm². The measurement of the leakage current from p-type layer to the substrate, shown in Fig.1 (d), indicates that the leakage current was less than 0.05% of the current flowing in the SiC resistor at an applied DC voltage of up to 2V. It should also be pointed out that, since p-type 4H-SiC was epitaxially grown on n-type 4H-SiC, the back-to-back p-n diodes would prevent the current from leaking into the substrate, which eliminates the contribution of the n-type 4H-SiC to the measurement of the piezoresistance in p-type 4H-SiC. The finite element analysis (FEA), shown in Fig.1 (e), demonstrates the distribution of electric field between two parallel electrodes. Evidently, the electric field mainly distributes between the two electrodes (more than 97%). Consequently, the influence of the currents flowing in different directions other than [1100] direction can be negligible.

The Young’s modulus of the 4H-SiC was characterized using three-point bending experiment shown in Fig.2 (a)-(b). From the relationship between the deflection δ of the SiC beam and the applied force F, the Young’s modulus E of 4H-SiC can be calculated by [18]:

\[ E = (FL^3)/(4wt^3\delta) \]

where \( L \) is the distance between two supporting points, \( w \) and \( t \) are the width and thickness of the beam, respectively. Accordingly, the Young’s modulus was found to be 503.7 GPa. To investigate the piezoresistive effect in p-type 4H-SiC, we utilized a simple and well-established bending beam method to induce uniaxial tensile strain into the piezoresistors as shown Fig.3 (a). This method has been used in a considerably large number of studies charactering the piezoresistive effect of semiconductors [11], [13], [16], [19]-[21]. 4H-SiC cantilevers, which are 45-mm-long, 5-mm-wide, and 0.35-mm-thick, were fixed at one end using an electrically insulated clamp, while the other end was deflected downwards by static forces. Let \( M \) be the bending moment generated by an external force, then the strain induced into the 4H-SiC piezoresistor is given by:

\[ \varepsilon = (Mt)/(EI) \]

where \( I \) and \( t \) are the inertial moment and thickness of the SiC cantilever, respectively. From the obtained Young’s modulus, for applied forces varying from 0 to 0.3 N, the strain induced into the 4H-SiC piezoresistor ranged from 0 to 182 µε. This was in good agreement with the FEA result using COMSOL® Multiphysics (Fig.2 (c)).

The GF of a p-type 4H-SiC piezoresistor is given by:

\[ GF = (\Delta R/R)/\varepsilon \]

where \( \Delta R \) is the resistance change of the unstrained resistance \( R \). Figure 3 (b) plots the relationship between the resistance change of 4H-SiC piezoresistors versus applied strain using the four-point probe measurement. Evidently, the measured resistance of the 100 µm-long 4H-SiC piezoresistors exhibited a good linearity under induced strain varying from 0 to 182 µε with linear regressions of 31.5 and -27.3 for longitudinal and transverse GFs, respectively. Table I lists the longitudinal and transverse GFs in [1100] direction with the length ranging from 100 to 300 µm. It can be seen that these measured GFs are comparable with the previous results of 3C-SiC [10]-[12], 6H-SiC [13], and n-type 4H-SiC [16]. The similarity of the measured GFs in SiC piezoresistors with different dimensions, listed in Table I, indicates that the strain induced on the top surface of the substrate was effectively transferred to the p-type layer. This was also consistent with the FEA of the strain induced to the p-type layer under bending (Fig.2 (c)).

To demonstrate the real-time data acquisition, the resistance change was converted to the output voltage of the Wheatstone bridge circuit (Fig.3 (c): Inset). In this measurement, the DC
bias input voltage was set to be 0.1V, therefore the Joule heating effect in the piezoresistor can be negligible [22]. Initially, the strain was increased from 0 to 182 με, showing an increase in the output voltage of the p-type 4H-SiC resistor (Fig.3 (c)). The output voltage decreased when decreasing the applied strain, then returned to 0 when the load was completely removed. A constant strain was also repeatedly applied then the piezoresistance of p-type 4H-SiC exhibited a good repeatability. These results remained almost the same in repeated measurements on different days. The repeatability and linearity of the piezoresistance of the as-fabricate p-type 4H-SiC piezoresistors indicate the potential for strain sensing applications.

| TABLE I |
| Longitudinal and Transverse GFs of P-type 4H-SiC |
| Length [μm] | Longitudinal GF | Transverse GF |
| 100 | 31.5 | -27.3 |
| 200 | 31.0 | -27.1 |
| 300 | 30.8 | -26.8 |

The positive longitudinal GF in [1100] direction exhibits a decrease in electrical conductance of p-type 4H-SiC under tensile strain, while the negative value of the transverse GF in this crystallographic orientation shows a positive trend. The electrical conductivity of p-type 4H-SiC can be simplified by [23], [24]:

$$\sigma = N_{hh}q \times \mu_{hh} + N_{lh}q \times \mu_{lh}$$

where $N$ is the hole concentration, $q$ is the unit charge, $\mu$ is the hole mobility, and the “$hh$” and “$lh$” subscripts stand for heavy holes and light holes, respectively. Under strain, the energy levels of heavy and light holes change, leading to the re-population of holes between these two bands. The decrease in the conductance of p-type 4H-SiC, under tensile strain along [1100] orientation, indicates that more charge carriers moved from the light hole band (with higher mobility) to the heavy hole band (with lower mobility). This also implies that the heavy hole band shifts upward to lower energy level, while the light hole band moves downward to higher energy level. On the other hand, the increasing conductance in the transverse direction under tensile strain shows that the heavy hole band moves downwards while the light hole band moves upwards. Therefore, the mobility of p-type 4H-SiC can be significantly enhanced by utilizing the transverse strain.

III. Conclusion

The piezoresistive effect of p-type 4H-SiC in [1T00] direction was characterized in which the longitudinal GF has a positive value of 31.5 while the transverse GF has a negative value of -27.3. The significantly high GFs found in p-type 4H-SiC demonstrate the potential for mechanical sensing applications. Additionally, it is confirmed that the mobility of p-type 4H-SiC based devices can be improved by employing strain engineering in the transverse direction.

ACKNOWLEDGEMENTS

This work was supported by the Queensland node of the Australian National Fabrication Facility, a company established under the National Collaborative Research Infrastructure Strategy to provide nano and micro-fabrication facilities for Australia’s researchers. The authors would like to thank Mr. Khanlou (Griffith University) for the assistance in the Young’s modulus measurement and Asst. Prof. Minh Le (Tohoku University, Japan) for the helpful discussion about the thermal annealing process.
REFERENCES


