Pushing the limits of piezoresistive effect by opto-mechanical coupling in 3C-SiC/Si heterostructure

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Abstract

This paper reports a giant opto-piezoresistive effect in p-3C-SiC/p-Si heterostructure under visible light illumination. The p-3C-SiC/p-Si heterostructure has been fabricated by growing a 390 nm p-type 3C-SiC on a p-type Si substrate using the low pressure chemical vapor deposition (LPCVD) technique. The gauge factor of the heterostructure was found to be 28 under a dark condition; however, it significantly increased to about -455 under illumination of 635nm wavelength at 3.0 mW/cm². This gauge factor is over 200 times higher than that of commercial metal strain gauge, 16 times higher than that of 3C-SiC thinfilm, and approximately 5 times larger than that of bulk Si. This enhancement of the gauge factor was attributed to the opto-mechanical coupling
effect in p-3C-SiC/p-Si heterostructure. The opto-mechanical coupling effect is the amplified effect of the photo-conductivity enhancement and strain-induced band structure modification in the p-type Si substrate. These findings enable extremely high sensitive and robust mechanical sensors and optical sensors at low cost, as no complicated nanofabrication process is required.

**Keywords**
3C-SiC, heterostructure, opto-piezoresistive, opto-mechanical coupling, gauge factor.

Strain effects in semiconductor devices have been studied extensively for numerous applications, such as, pressure sensor, force sensor, and inertia sensor, owing to their superior ability to alter the electronic structure, and carrier mobility. Piezoresistive effect is one of the most commonly employed strain sensing techniques, thanks to its high sensitivity, simple read-out circuit, and low power consumption. Silicon (Si) is the most studied material as piezoresistive material due to its commercial availability, mature fabrication technologies, and high gauge factor (GF).

Recently, the piezoresistive effect in large band gap materials have been of interest for applications in harsh environments. Among these materials, SiC emerged as a promising candidate courtesy of its high bandgap and excellent mechanical and chemical properties. The gauge factors of the piezoresistive effect in SiC have been reported to be approximately 30, which is approximately four times smaller than Si. To enhance the sensitivity, scaling down the piezoresistor to a nanometer-scale has drawn significant attention recently. Motivated by the work of He and Yang, which reported a giant piezoresistive effect in top down fabricated Si nanowires, a number of studies have been carried out to investigate the scale effect in the piezo-resistance of SiC nanowires. Bi et al. reported a transverse gauge factor of (∼) 47 in n-type 3C-SiC nanowires (width ∼ 230 nm), which is significantly higher than that in bulk 3C-SiC. This enhancement is attributed to strain-induced changes in
the surface states in nanowires. Another method has recently been reported to enhance the sensitivity of 3C-SiC nanowires, which consists of a nano thin film released from the substrate.\textsuperscript{17}

Moreover, a giant piezoresistive effect can be achieved when nanowire size is diminished to lower than 10 nm, where charge mobility and surface-area-to-volume ratio is high.\textsuperscript{21} Li et al. obtained a giant GF in SiC nanowires by applying a loading force of a conductive AFM tip.\textsuperscript{18} But, as the strain was applied by an AFM tip, the stress may be induced only in the pressed area. Most importantly, extremely sophisticated techniques are required to fabricate sub-nano wires. Furthermore, the giant piezoresistive effect in nanowires is due to dynamic properties of surface state, which varies with time, therefore, the large GF in nanowires is still controversial.\textsuperscript{17,22} On the other hand, our work demonstrates giant piezoresistive effect in a large area of thin heterostructure, which is unprecedented.

To date, most of the studies on piezoresistive effect are mainly focused on the mono functioning layer, but the influence of bottom substrate of a heterostructure on piezo-sensitivity has not been elucidated. In this paper, we report, for the first time, the possibility of enhancing the sensitivity of an iso-type 3C-SiC/Si heterostructure using the opto-mechanical coupling effect. The experimental data showed that a maximum GF of 455 was achieved at an illumination of 3.0 mW/cm\textsuperscript{2} (635nm), whereas the GF was only 28 in dark conditions. Moreover, since the Si substrate is fully covered by 3C-SiC, the heterostructure would be applicable in a harsh environment, such as, highly corrosive and high pressure environments. The proposed structure is also prepared on a large surface area, indicating that it does not require any sophisticated and advanced processing to make nano-scale devices for enhancing sensitivity. Therefore, this study reveals a simple and effective way to boost the sensitivity of the device with the help of suitable light conditions.

A thin 3C-SiC film with a thickness of 390nm was epitaxially grown on p-Si (100) substrate by using a custom-made low pressure chemical vapor deposition (LPCVD) reactor at 1000°C; utilizing \(SiH_4\) and \(C_2H_2\) as precursors.\textsuperscript{23} Trimethylaluminium [(CH\textsubscript{3})\textsubscript{3}Al] was used
as p-type in situ doping. Details of the growth process have been discussed in a supplementary document. The carrier concentration of 3C-SiC film and Si substrate were found to be $5 \times 10^{18} \text{ cm}^{-3}$ and $5 \times 10^{14} \text{ cm}^{-3}$, respectively, using the hot probe and Hall effect measurement techniques. Figure 1a shows the X-ray diffraction analysis, which illustrates that 3C-SiC film was epitaxially grown on Si substrate. The grown SiC was single crystalline which was confirmed by the Selected Area Electron Diffraction (SEAD) (Figure 1c). The TEM image (Figure 1b) shows that there are some stacking fault defects near to the SiC and Si interface. These defects caused by the lattice and thermal expansion mismatch between 3C-SiC and Si.

Al electrodes were deposited on 3C-SiC and patterned to form resistors and then the wafer was diced into beams with dimensions of $40 \text{ mm} \times 5 \text{ mm} \times 0.625 \text{ mm}$ for bending experiments. The I-V curve shows a linear trend, which indicates that Al formed a good ohmic contact with the SiC film (Figure 2).

The opto-piezoresistive effect in 3C-SiC/Si heterostructure was measured using the experimental setup as shown in Figure S1 (supplementary document). The performance of
Figure 2: Characteristics of the heterostructure in dark environment: I-V curve of the heterostructure in dark condition (inset: zoom-in of the current through the 3C-SiC/Si junction).

The heterostructure was investigated under various 635nm (THORLAB S1FC635) illumination intensities. Figure 3a shows the relative resistance change of the device under different mechanical stresses in [110] direction at various light conditions. It was observed that the relative resistance change in 3C-SiC showed a linear behaviour to the applied tensile stresses. The GF of the heterostructure, in dark conditions, was found to be 28. However, the change in relative resistance increased significantly under illumination, for instance, the GF was measured to be about -416 under 2.0 mW/cm² (635nm) illumination, which is approximately 15 folds that in dark environments (Figure 3b). This gigantic boost in gauge factor may be attributed to the absorption of light in 3C-SiC layer that enhances the sensitivity of the devices or/and Si-substrate starts to contribute to the overall device sensitivity.

In order to gain insight into this phenomenon, we transferred the 3C-SiC thin-film from Si to glass substrate using the FIB (Focused Ion Beam) technique (details of transferring process have been reported in24). It was observed that the resistance of the transferred 3C-SiC thin film remained almost constant under different illumination intensities (635 nm), reflecting that due to the large band gap, 3C-SiC is insensitive to the applied illumination (See supporting information, Figure S4).
Figure 3: (a) Relative resistance changes of the device as a function of strain and (b) gauge factor at different light conditions (inset shows the repeatable response of the heterostructure at different strains (0 ∼ 346 ppm) under 1.0 mW/cm² illumination (635nm)).

For further clarification, we measured current through the heterojunction in dark conditions (Figure 2). As observed, only 0.1% of the total current flowed through the heterojunction, indicating that only 3C-SiC acts as the functioning layer and hence the GF of the device was found to be as low as 28, i.e., similar to the GF of p-type 3C-SiC thinfilm.\textsuperscript{5,10,25} Therefore, the high GF of over -450 obtained under illumination must come from Si substrate and the 3C-SiC/Si heterostructure.

The underlying physics behind this huge modulation in strain sensitivity under illum-
Figure 4: (a) Electron-hole pair generation and separation in Si-substrate under light illumination and schematic band diagram of 3C-SiC/Si hetero-structure at (b) terminal A (negative bias) and (c) terminal B (positive bias). The band offset values were taken from ref.\textsuperscript{26}.

...nation can be explained according to band diagram analysis (Figure 4). The band diagram of 3C-SiC/Si heterostructure at terminal A is shown in Figure 4b. Under the illumination, electron-hole (e-h) pairs are generated in Si-substrate due to the absorption of incident light. When a negative potential was applied at point A, the 3C-SiC band edges moved upward and hence the hole tunnelling barrier width became smaller (Figure 4b). In addition, when uniaxial tensile stress was applied to the heterostructure, degeneracy lifted and the valance bands were also wrapped as shown in Figure 5.\textsuperscript{27} Heavy hole band ($E_{hh}$) shifted to a higher energy level compared to light hole band ($E_{lh}$) because it has a larger strain effective mass.\textsuperscript{28,29} Applied tensile stress also reduced the net band splitting between $E_{lh}$ and $E_{hh}$, hence holes were repopulated from $E_{hh}$ to $E_{lh}$.\textsuperscript{30,31} Due to the hole repopulation, total effective mass decreased because light hole effective mass is smaller than that of heavy hole. Furthermore, as observed from Figure 5c, the tunnelling barrier height ($\phi$) of light hole is
Figure 5: Schematic diagram of energy band structure in k space (a) unstressed and (b) under tensile stress in [110] direction. (c) Hole repopulation in valence bands of the structure under stress.

smaller than that of heavy hole and hence the effective tunnelling barrier height also decreased. Moreover, from the Drude model, it is known that the carrier mobility is inversely proportional to the effective carrier mass \( \mu \propto 1/m^* \). Therefore, due to an increase in carrier mobility and decrease in tunnelling barrier height, the hole tunnelling probability increases with uniaxial tensile stress and hence the conductivity of the heterostructure will increase with stress.

The band diagram of 3C-SiC/Si heterostructure at terminal B is shown in Figure 4c. When a positive potential was applied at terminal B, the electrons were enticed from the Si-substrate to 3C-SiC mainly because of thermoionic emission over the potential barrier. In addition, when stress is induced in the 3C-SiC/Si heterostructure, the conduction band edges of both materials can shift in either direction, which depends on the crystal orientation and direction of applied stress. As we observed, the current through the junction increases with stress, as such, we can consider that the conduction band offset \( \Delta E_C \) decreases with increasing stress. Therefore, the potential barrier \( V_B = \Delta E_C + qV_b \) for thermoionic emission of electron decreased with stress, indicating that the probability of an electron reaching
to SiC layer increases with stress and hence the conductivity of the heterostructure increases. As a result, a large gauge factor was observed under light. It is interesting to note that the GF of the device became negative under illumination, whereas, it was positive in dark conditions. This is because, under illumination, additional e-h pairs generated in Si-substrate which are attracted to the opposite potential terminal of 3C-SiC. In addition, the hole tunnelling at terminal A and electron flow at terminal B both increased with stress. Therefore, overall conductivity will increase significantly under stress and light illumination.

Furthermore, with the increase of illumination intensity, the amount of e-h pair generation increases and the tunnelling barrier width decreases (barrier width ($W_d$) is inversely proportional to the carrier concentration ($N_a$)) as shown in Figure 5. Therefore, the probability of carrier tunnelling under stress from Si to 3C-SiC layer increased further. As shown in Figure 3, the (GF) enhanced more than 270% when light intensity increased from 1.0 $mW/cm^2$ to 3.0 $mW/cm^2$.

In conclusion, this work has demonstrated an unprecedented approach to boost the sensitivity of piezoresistive-based sensors through the opto-mechanical coupling effect in 3C-SiC/Si heterostructure. The experimental data showed that the strain sensitivity increased up to 1600% under a suitable light illumination. The underlying mechanism for significant improvement in the gauge factor is attributed to the light-generated electron-hole (e-h) pairs and the strain-induced shifts of valance sub-bands in Si-substrate, leading to the increase of charge carrier mobility and decrease of tunnelling barrier height. Therefore, the hole tunnelling at negative-biased junction and electron flow at positive-biased junction increased with tensile stress, hence, the conductivity of heterostructure increased with tensile stress. As a result, a negative gauge factor was observed. With the increase of light intensity, more carriers would be generated in Si substrate, leading to higher probability of carriers tunnelling, and therefore, further increase of the gauge factor. This significant finding enables development of extremely high-sensitive mechanical sensors and photodetectors based on p-3C-SiC/p-Si heterostructure.
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Supporting Information Available

Device fabrication procedures are discussed in the growth process section. Fabrication process of 3C-SiC/Si resistor in Figure S1, experimental setup is shown in Figure S2, the repeatability of device response is shown in Figure S3, and the variation of the transferred 3C-SiC on glass under the illumination of 635 nm is shown in Figure S4.

References


Graphical TOC Entry
Supporting Information

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3C-SiC growth process

The p-type single crystalline SiC was epitaxially grown on Si-substrate by a Low Pressure Chemical Vapor Deposition (LPCVD) technique.\textsuperscript{1–3} SiH\textsubscript{4} and C\textsubscript{2}H\textsubscript{2} were employed as precursors. (CH\textsubscript{3})\textsubscript{3}Al (TMAI) was used for introducing p-type \textit{in situ} doping in 3C-SiC. The ASE (alternating supply Epitaxy) method was utilized for epitaxial growth of SiC. When SiH\textsubscript{4} was supplied, Si atoms were absorbed on the SiC surface and arranged themselves in a self-assembled pattern. Then, with the supply of TMAI, Al atoms were absorbed on the Si-terminated surface (Al-CH\textsubscript{3} bonds break below 527\textdegree C).\textsuperscript{4} Finally, when C\textsubscript{2}H\textsubscript{2} was introduced, the absorbed Al and Si atoms were converted into 3C-SiC layers. For electrical measurements, the aluminium electrodes were deposited on top of 3C-SiC and back of Si-substrate by using photolithography and sputtering processes.
Figure S1: Process flow to fabricate 3C-SiC/Si beam: (a) Crystal plane and orientations of the epitaxially grown 3C-SiC on (100) Si wafer, (b) deposition of Al layer using a metal sputtering machine, (c) the Al layer was patterned to form the electrodes on 3C-SiC, and (d) dicing of the wafer along [110] direction to form (e) 3C-SiC/Si beam for bending experiment.
Figure S2: A schematic diagram of the experimental setup used to characterize the opto-piezoresistive properties of the heterostructure. One end of the cantilever was fixed on the optical air table with the help of a 3D mechanical stage. The sample position and light focus point can be adjusted by x-y-z stage at a resolution of 1 µm. A 635nm (THORLAB S1FC635) laser source was used to evaluate the performance of the device at various light intensities. To eliminate the effect of Joule heating, a small current of 100 µA was applied from (Agilent)™ 344110A Multimeter. The inset in Figure S2 is a cut-away view of the device, showing aluminum electrodes, SiC layer and Si substrate.
Figure S3: Resistance variation of the device at different light intensities under no load condition. As observed, the conductivity increased with the increase of light intensity due to the generation of carriers and the resistance reaches to the initial value when the light is turned off, indicating that the device has high reproducibility.
Figure S4: The variation in resistance of 3C-SiC/glass resistor under 635 nm illumination and we observed that the transferred 3C-SiC resistor is almost insensitive to the applied light condition.

References


