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Opto-electronic coupling in semiconductors: towards ultrasensitive pressure sensing

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The discovery of giant piezoresistive effect in a semiconductor heterojunction by optoelectronic coupling can open a new era for mechanical sensors. This paper develops a novel concept of opto-electronic coupling in semiconductor heterojunctions for pressure sensing. We employ non-uniform illumination of visible light on a SiC/Si heterojunction to generate a gradient of charge carriers in the SiC nanofilm. These charge carriers are then manipulated by a tuning current, producing giant relative resistance changes of the material under applied pressure. We successfully demonstrated the enhancement by opto-electronic coupling in a SiC/Si heterojunction pressure sensor to amplify its sensitivity up to 185,000 times compared to the unilluminated condition. In addition, the opto-electronic coupling has significantly improved the repeatability, stability, signal-to-noise ratio and detectable range of the pressure sensor. The ultrahigh sensitive pressure sensing mechanism by opto-electronic coupling will pave a way for development of extremely sensitive mechanical sensors.

Introduction

Pressure sensors are considered as one of the most prominent microelectromechanical system (MEMS) devices^{1,2} with diverse applications in robotics, healthcare^{3–7}, automobile industry⁸, homeland security⁹, energy harvesting^{10,11} and environmental monitoring^{3,9,12}. Detection principles such as piezoresistive^{3,12–14}, piezoelectric¹⁵, capacitive^{5,16,17}, and optical concepts^{18–20} have been applied to realize high-performance pressure sensors. Among these concepts, the piezoresistivity that transforms mechanical deformation into a resistance change has various advantages such as a wide linearity range¹, easy integration, small size, simple device fabrication process³, and low power consumption¹².

It is desirable to modulate performances of piezoresistive pressure sensors, particularly in sensitivity, durability, reliability, linearity, and response time. To date, pressure sensors have achieved substantial advancement in performance. Conventional enhancement approaches have focused on optimizing designs such as the geometry of diaphragms, and the location and direction of piezoresistors. Recently, performances of pressure sensors have been significantly improved by using nanostructures such as nanowires^{14,21,22}, nanotubes^{13,16}, nanofibers¹⁸ and nanopar-

ticles²³. For instance, by utilizing SiC nanowire, Phan et al.¹⁴ enhanced the sensitivity of the pressure sensor 3-fold in comparison to conventional structures. In terms of material, while silicon (Si) is the most prominent material used for piezoresistive pressure sensors owing to its high piezoresistive effect, excellent mechanical properties, and compatibility with advanced microfabrication technologies⁸, silicon carbide (SiC) with properties of high energy band gap, chemical inertness and high stiffness is a promising material that may work reliably in harsh environments^{24–28}.

More recently, several tuning approaches have been proposed, not only for improving pressure sensitivity, but also for different sensing applications^{4,15,23,29–31}. By controlling the mechanical properties of sebacic acid and glycerol in the synthesis process, Clementine et al.³¹ successfully developed a biodegradable pressure sensor array of a sensitivity of 0.76 kPa⁻¹ for blood vessel monitoring. Another example was an improvement in sensitivity, by 3.5 times, of a tough flexible sensor based on monolayer-copper nanoparticles by decreasing width of the substrates from 30 mm to 10 mm²³. Additionally, Gregor et al.⁴ demonstrated a flexible polymer transistor with tuneable sensitivity for pressure sensing. The pressure sensitivity was modulated approximately 8 times as the source drain voltage (V_{DS}) decreased from -80 V to -10 V at the low pressure range (< 1 kPa), and the sensitivity was found to be highest at V_{DS} of -40 V in the higher pressure regime. This maximum sensitivity remained over the entire pressure regime (from 0.1 kPa to 10 kPa) as the source drain voltage was approximately -40 V.

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Fig. 1 Pressure sensing enhancement mechanism by opto-electronic coupling in a heterostructure pressure sensor.

The discovery of a giant piezoresistive effect in SiC/Si heterojunction by opto-electronic coupling can create a new direction for development of mechanical sensors³². In this paper, we demonstrate a tremendous enhancement in performance of a micromachined 3C-SiC/Si heterojunction pressure sensor by opto-electronic coupling (Figure 1). The pressure sensitivity is boosted from $4.7 \times 10^{-6} \text{ kPa}^{-1}$ to as high as 0.87 kPa^{-1} utilizing opto-electronic coupling, which is approximately 185,000 times improvement in comparison with the pressure sensitivity in the case without applying opto-electronic coupling. This sensitivity is 1700 times higher than that of the most sensitive semiconductor-based piezoresistive pressure sensors to date. In addition, the repeatability, stability, signal to noise ratio (SNR), and detectable pressure range were significantly improved by opto-electronic coupling as well. Furthermore, this novel sensing mechanism substantially facilitated fabrication process and created a 3C-SiC protection layer for harsh environment applications.

Design and sensing concept

We implemented a pressure sensor with a highly doped p-type 3C-SiC/p-type Si (p^+ -3C-SiC/p-Si) heterojunction diaphragm. Details of the design are shown in Supplementary Figure S1. The sensing element was located at the middle of a diaphragm edge

and aligned in [110] direction, which possesses the maximum piezoresistive coefficient in p-type 3C-SiC. Applied pressure was detected via changes in resistance of the sensing element. Opto-electronic coupling was realized by non-uniformly illuminating the sensing element with visible light with most of the incident light struck area around electrode A. Combining with illumination, a controlled current was supplied to modulate the carrier energy. By optimizing value of the tuning current versus the illumination condition, the pressure sensor performance was enormously enhanced.

Fabrication process

Growth 3C-Si nanofilm on Si substrate. From a p-type single crystalline Si (100) substrate, we deposited a thin film 3C-SiC on a p-type single crystalline Si (100) substrate by a Low Pressure Chemical Vapor Deposition (LPCVD) technique at 1000°C using silane and propene as a precursor compound. Aluminum atoms from trimethyl-aluminum were then doped into the 3C-SiC thin film in the *in situ* growth process to form a heavily doped 3C-SiC layer. Thickness of the 3C-SiC film was approximately 300 nm determined by NANOMETRICS Nano-spec-based measurement with the tolerance of less than $\pm 1.5 \text{ nm}$ over the whole diaphragm. Geometry of the diaphragm was approximately $5 \text{ mm} \times 5 \text{ mm} \times 225 \mu\text{m}$. Acceptor concentrations in the 3C-Si thin film, measured by the hot probe and Hall effect techniques, was $5 \times 10^{18} \text{ cm}^{-3}$. Supplementary Figure S2 shows characteristics of the 3C-SiC thin film grown on the Si substrate, which indicates that 3C-SiC was epitaxially grown on the Si substrate.

Sensor fabrication. As shown in Figure 2, $5 \times 5 \text{ mm}^2$ windows were opened at the backside of the SiC/Si wafer using anisotropic wet etching in a solution of 25% KOH with an etching rate of approximately $70 \mu\text{m}/\text{hour}$ to form diaphragm of the pressure sensor. The subsequent sputtering process deposited an aluminum layer on the surface of the 3C-SiC film. Next, aluminum was patterned through a lithography process to form the sensing element, which was defined by two aluminum electrodes. The wafer was rapidly thermal-annealed to obtain Ohmic contacts between aluminum and 3C-SiC, following by final step which diced the wafer into smaller pressure sensors. The sensors were then attached to chip holders with an open window at the center using an epoxy adhesive, as depicted in Figure S3-a. Supplementary Figure S3-b presents the Scanning Electron Microscope (SEM) image from the back of diaphragm after wet etching. The root mean square roughness of the diaphragm top surface, estimated by Atomic force Microscopy, is less than 20 nm. As the formation of the sensors does not request any dry-etching of the sensing element, fabrication process of the pressure sensor was significantly simplified compared to those of conventional piezoresistive pressure sensors^{1,14}. In addition, the 3C-SiC layer can play a role as a protection layer for the Si substrate in harsh environment applications.

Performance Characterization

Supplementary Figures S4-a and S4-b respectively show the experimental schematic and setup to investigate performances of the pressure sensor. Air pressure was applied to backside of the di-

Fig. 2 Fabrication process. First, 3C-SiC nanofilm was epitaxially grown on a (100) Si substrate. Then, the diaphragm was formed via a wet etching process in a solution of 25% KOH. Next, aluminium electrodes were patterned on the top of the 3C-SiC nanofilm layer via consecutive steps including depositing aluminium on the top of 3C-SiC nanofilm, coating photoresist on the top of aluminium layer, exposing the wafer to ultraviolet light, and etching aluminium. Finally, the pressure sensors were separated via dicing process and then attached on chip holders.

aphragm using an ELVEFLOW OB1 pressure controller combined with a pneumatic pump. The sensor was covered by a black acrylic frame to eliminate the influence of surrounding uncontrolled light. The incident light with intensity of approximately 20,000 lx illuminated the sensing element through a small window on the black acrylic frame. A KEITHLEY 2450 Source Meter was used to control the tuning current and simultaneously measure the output voltage. Before conducting the experiment, position of the light was accurately adjusted by measuring feedback signal from the lateral photovoltage. The repeatability of the lateral photovoltage and photo current as the light periodically turned ON and OFF are shown in Supplementary Figures S5-a and S5-b. Under the illuminated condition, the lateral photovoltage and photocurrent are approximately 25 mV and 68.2 μ A, respectively, and the supplied current of 68.2 μ A was observed as the optimal tuning current.

Results and discussion

Pressure sensitivity is defined as

$$S = \frac{\Delta V}{V_0} \cdot \frac{1}{P} \quad (1)$$

where $\Delta V = V - V_0$ is the change of voltage across the sensing element due to applying pressure; V_0 is the voltage across the sensing element under pressure-free condition; P is the applied pressure. To demonstrate an unprecedented modulation of the pressure sensitivity using opto-electronic coupling, the pressure sensitivity was evaluated in both unilluminated condition (i.e., without opto-electronic coupling) and illuminated condition. The supplied current was constantly controlled at 68.2 μ A. As shown

in Figure 3, the average pressure sensitivity was approximately $4.7 \times 10^{-6} \text{ kPa}^{-1}$ under the unilluminated condition (Figure 3-a) and this sensitivity was enhanced to as high as 0.87 kPa^{-1} under the illuminated condition (Figure 3-b), which was an enormous enhancement (approximately 185,000 times enhancement). The sensitivity of our sensor is more than 1,700 times higher than the best result of recently reported micromachined semiconductor pressure sensors (Supplementary Table S1). This huge improvement in sensitivity might result from the modulation of piezoresistive effect by opto-electronic coupling³². Moreover, this sensitivity can be further improved by decreasing thickness of the diaphragm as the current thickness (225 μm) is much larger than that of previous reports (70 μm and 150 μm)^{1,33}. This huge improvement in sensitivity compared to previous report totally came from the opto-electronic coupling, as the sensitivity of our sensor under the unilluminated condition is consistent with those of previous reports.

Under the illuminated condition, the tuning current was supplied so that the total current running across the sensing element was approximately 68.2 μ A and this current was kept constant throughout the experiment. Therefore, the change of voltage across the sensing element is

$$\frac{\Delta V}{V_0} = \frac{V - V_0}{V_0} = \frac{R - R_0}{R_0} = \frac{\Delta R}{R_0} \quad (2)$$

where R_0 and R are the resistance across the sensing element under pressure-free condition and under the applied pressure, respectively. Apparently, from equation (2), the change of voltage across the sensing element is proportional to the change of resistance across the sensing element. In the other words, the change

Fig. 3 Pressure sensitivity enhancement by opto-electronic coupling. (a) The pressure sensitivity is $-4.7 \times 10^{-6} \text{ kPa}^{-1}$ under unilluminated condition. (b) The sensitivity was unprecedentedly enhanced to -0.87 kPa^{-1} by opto-electronic coupling. Due to opto-electronic coupling, the pressure sensitivity was improved approximately 185,000 times which is 1,700 times higher than the best value of the recently reported silicon-based pressure sensor. The relationship between output voltage and the applied pressure (c) under dark condition and (d) under light condition. Under the unilluminated condition, the absolute change of the output voltage was approximately $3.9 \mu\text{V}$ as the applied pressure change from 30 kPa to 70 kPa. Under the same pressure range, the change of the voltage was $330 \mu\text{V}$ under the illuminated condition. (e) Repeatability of the fractional change in voltage under unilluminated condition which was approximately 1.5×10^{-4} , 2.1×10^{-4} , 2.6×10^{-4} under 40, 50, and 60 kPa, respectively. (f) Repeatability of the fractional change in voltage under illuminated conditions while the tuning current was kept constant at $68.2 \mu\text{A}$ and the air pressure was applied and released at a frequency of 0.1 Hz. The repeatability was excellent, and fractional changes in the voltage are as high as 19, 28.7, 41.3, 54.6 and 69.5 under applied pressures of 30 kPa, 40 kPa, 50 kPa, 60 kPa, and 70 kPa, respectively which were enormous enhancements from the unilluminated condition.

of the voltage depends only on the piezoresistive effect, which is enhanced by opto-electronic coupling³².

The relationships between output voltage and the applied pressure under the unilluminated and illuminated conditions are shown in Figure 3-c and 3-d. Under the unilluminated condition, the absolute change of the voltage was approximately $3.9 \mu\text{V}$ as the applied pressure increased from 30 kPa to 70 kPa, while the change under the illuminated condition was approximately $330 \mu\text{V}$ under the same pressure range. Figures 3-e and 3-f present the voltage signal responding to various applied pressures, which were loaded and unloaded at a frequency of 0.1 Hz under the unilluminated and illuminated conditions. For example, under applied pressure of 50 kPa, the fractional change in voltage was approximately 2.1×10^{-4} under the unilluminated condition, and this value tremendously increase to 41.3 under the illuminated condition. It is obvious from Figures 3-c and 3-d that response under the illuminated condition was much greater and more stable than that under the unilluminated condition. Signal-

to-noise ratio (SNR) was also significantly improved by utilizing opto-electric coupling.

The sensitivity was tuneable by controlling the supplied current under the illumination (red line in Supplementary Figure S6) but remained constant under the unilluminated condition (blue line in Supplementary Figure S6). Under the illuminated condition, the sensitivity increased from $5.1 \times 10^{-4} \text{ kPa}^{-1}$ to $1.22 \times 10^{-2} \text{ kPa}^{-1}$ when the tuning current rose from $50 \mu\text{A}$ to $67.4 \mu\text{A}$, which corresponds to the positive regime (Supplementary Figure S6-b). This sensitivity increased tremendously to reach the maximum value (approximately 0.87 kPa^{-1}) as the tuning current was increased to $68.2 \mu\text{A}$ (Supplementary Figure S6-c). As shown in Supplementary Figure S6-d, when the tuning current moved further from the optimal value, the sensitivity decreased significantly to $3.92 \times 10^{-4} \text{ kPa}^{-1}$ at $90 \mu\text{A}$ tuning current. These results indicate that coupling the incident light with the tuning current significantly improved and tuned sensitivity of the pressure sensor. The unprecedented enhancement in sensitivity by opto-electronic

Fig. 4 (a) Generation and redistribution of charge carriers. Under the light illumination, EHPs were generated in the Si substrate and depletion region, then photogenerated holes were injected into 3C-SiC by the internal built-in electrical field across the depletion region and/or the tunneling mechanism. Due to the non-uniform illumination, the holes migrating into the SiC nanofilm were different in the lateral direction which results in a gradient of hole concentration between the two electrodes in the 3C-SiC nanofilm layer. This formed a lateral photovoltage between electrode A and electrode B, which was proportional to the Femi level difference in the 3C-SiC nanofilm layer at the two electrode regions. **(b) Valence band configuration in the 3C-SiC nanofilm with biased electric field and applied pressure.** Under the light illumination, Femi levels of 3C-SiC at electrodes A and B were the red lines. As a tuning current was supplied from electrode A to electrode B, an external electric field applied between the two electrodes modulated energy of the charge carriers. Femi levels in the 3C-SiC nanofilm at the two electrode regions were shifted in opposite directions (the blue lines). The supplied current was optimized so that Femi levels in the 3C-SiC nanofilm were balanced, thus voltage across the sensing element was relatively small under the pressure-free condition. Under applied pressure, valence bands of light holes were shifted upwards while those of heavy holes were relocated downwards (green lines), which redistributed the charge carriers between light hole and heavy hole sub-bands.

coupling can be attributed to the following three main factors.

First, under the illumination, photons were injected to excite charge carriers (electrons/holes) in the 3C-SiC/Si heterojunction and the Si substrate while the 3C-SiC nanofilm was transparent to visible light. Some electrons absorbing sufficient energy became free electrons and simultaneously leaved holes behinds, which called photogenerated electron/hole pairs (EHPs). In the heterojunction region, these photogenerated electrons/holes were separated by an internal built-in electric field, where the photogenerated holes and electrons moved toward the 3C-SiC nanofilm and Si substrate, respectively. In addition, photogenerated holes in the Si substrate hypothetically migrated to the 3C-SiC layer by the tunnelling mechanism (Figure 4-a). As a consequence,

the hole concentration in 3C-SiC increased. Under non-uniform illumination, the photogenerated holes migrated into 3C-SiC differently in lateral direction, hence resulting in a gradient of hole concentration within the 3C-SiC nanofilm. This process formed a voltage known as lateral photovoltage V_{photo} between two electrodes A and B of the sensing element that is proportional with the Femi energy difference in 3C-SiC between the two electrode areas ($eV_{photo} = F_{SiC@B} - F_{SiC@A}$) (Figure 4-b). When two electrodes A and B were shorted, the short-circuit photocurrent flow is shown in Figure S8-a.

Second, by supplying a tuning current I from electrode A to electrode B of the sensing element, an external electrical field E

Fig. 5 Stability of the pressure sensor. A cyclic test was conducted in two consecutive days by turning ON and OFF pressure of 60 kPa under the stabilized illuminated condition and the tuning current was kept constantly at $68.2 \mu\text{A}$. **(a)** Voltage signal in 1000 seconds on the first day. **(b)** Voltage signal in 1000 seconds on the second day. Enlarged views at the initial seconds **(c)** and the final seconds **(d)** of the 1000 second recorded duration. It is obvious that the pressure sensor worked stable throughout the long test duration under the illuminated condition.

was formed

$$E = \int_0^L I \cdot \frac{1}{\sigma} dx \quad (3)$$

where x is the distance from electrode A, L is length of the piezoresistor, and σ is conductivity of 3C-SiC. This external electric field E changed energy of the charge carriers (holes in this work), hence redistributing the carriers in the 3C-SiC layer. Con-

sequently, the Femi energy difference was counteracted, creating a small voltage drop in the sensing element under pressure-free condition. The magnitude of the voltage V_0 was proportional to the Femi level difference in 3C-SiC at the two electrode regions as depicted by blue lines in Figure 4-b. When the tuning current was optimized, a small initial voltage of the sensing element $V_0 \approx 0$ was observed under pressure-free condition. In addition,

Fig. 6 Expansion of detectable pressure regimes. Responses of the pressure sensor in the low-pressure regime under the unilluminated condition (a) and under the illumination (b). While it was unable to distinguish pressure below 30 kPa under the unilluminated condition, the sensor could detect low pressure down to 5 kPa due to opto-electronic coupling. Unlike conventional methods such as creating diaphragms thinner or larger, which make pressure sensors weaker, opto-electronic coupling does not affect robustness of the sensor.

by optimizing the tuning current, influence of the photocurrent to the change of the output voltage was also eliminated as shown in section 9 in supplementary document.

Third, when a pressure was applied to the backside of the diaphragm, a compressive strain was induced in the sensing element. This shifted valance bands of the light holes upward to lower energy levels and of the heavy holes downward to higher energy levels (green lines in Figure 4-b). Since charge carriers tend to occupy at lower energy bands, light holes and heavy holes were redistributed in the energy sub-bands, resulting in a decrease in heavy hole concentration and an increase in concentration of light holes. Since a light hole has a lower effective mass than a heavy hole, the decrease in heavy hole concentration and the increase in light hole concentration resulted in a decrease in total of the effective mass. Consequently, mobility of the holes, on average, increased, leading to a decrease in resistance of the material.

To evaluate the stability over time of the pressure sensor, we conducted a cyclic test by applying and releasing an air pressure of 60 kPa at a period of 10 seconds in two consecutive days with a 1000 second duration in each day. In this cyclic test, the illuminated condition was stably fixed, and the tuning current remained constant at the optimal value of 68.2 μ A. Figure 5 shows the voltage signals recorded in the two days and enlarged views at initial seconds (Figure 5-c)and final seconds of the cyclic test (Figure 5-d). It is obvious that performance of the pressure sensor shows negligible degradation over the long test duration.

We further demonstrated that opto-electronic coupling enhanced stability of the sensor by studying stability of the sensors under the unilluminated condition. As shown in Supplementary Figure S10, although absolute change of the voltage was stable, the signal significantly drifted after the long test duration. Drifting under the unilluminated condition and stability under the illuminated condition can be explained as follows. When the current

was supplied to the sensing element, the device temperature varied because of Joule heating effect and/or changes of surrounding environment (such as temperature or humidity), resulting in the generation of EHPs. Consequently, electric conductivity of the sensing element changed, hence the resistance drifted under the unilluminated condition. In contrast, under the illuminated condition, amount of EHPs generated by the temperature variation was imperceptible with that generated by the photon absorption. Therefore, the electrical conductivity was stable under the illuminated condition.

Real-world applications of a pressure sensor benefit from expansion of detectable range, particularly to a lower pressure regime. Conventionally, diaphragms were designed thinner or larger. However, this method will reduce robustness of sensors as well as upper limit of applied pressure. It will be more valuable if methods can expand the pressure detectable range but do not affect the robustness of the sensor. Figure 6 compares detectable range of the pressure sensor under the illuminated and unilluminated conditions. Under the illuminated condition, the lowest pressure that the sensor was able to be detected was as low as 5 kPa, while it was impossible to measure pressure under 30 kPa under the unilluminated condition. As such, by utilizing opto-electric coupling, the measurable pressure range was expanded while the robustness was maintained. The expansion of detectable range was contributed to significant improvement of the sensitivity and stability over time.

Conclusion

In conclusion, we have demonstrated pressure sensing enhancing mechanism via opto-electronic coupling resulting in an unprecedentedly sensitive based-semiconductor pressure sensor. Because of opto-electronic coupling, sensitivity, stability and SNR of the pressure sensor were significantly improved, and the detectable range was expanded. The unprecedented sensitivity in compari-

son to well-known silicon MEMS pressure sensors is a result of an enormous enhancement in performance of the pressure sensor. By applying opto-electronic coupling, sensitivity of the pressure sensor has been modulated by more than 185,100 times and more than 1,700 higher than values of recently reported silicon-based pressure sensors. In addition, the new pressure sensing mechanism significantly simplified fabrication process of the pressure sensor and enable possibility of applications in harsh environment. Enhancing performance of the pressure sensors resulted from the generation charged carriers on bottom layer and depletion region of the heterojunction structure, injections and redistribution of holes on the nanofilm under the light illumination which were combined with modulating energies of the charged carriers under the tuning electrical current and shifting sub-band energies under applying pressure. Our method was successfully demonstrated on an ultrahigh sensitive 3C-SiC/Si heterojunction pressure sensor. We envision that opto-electronic coupling can be applied for the development of ultra-sensitive and stable mechanical sensors with other materials and structures.

Conflicts of interest

The author declare no competing financial interests.

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