Enhancing the piezoresistive effect is crucial for improving the sensitivity of mechanical sensors. Herein, we report that the piezoresistive effect in a semiconductor heterojunction can be enormously enhanced via optoelectronic coupling. A lateral photovoltage, which is generated in the top material layer of a heterojunction under non-uniform illumination, can be coupled with an optimally tuned electric current to modulate the magnitude of the piezoresistive effect. We demonstrate a tuneable giant piezoresistive effect in a cubic silicon carbide/silicon heterojunction, resulting in an extraordinarily high gauge factor of approximately 58,000, which is the highest gauge factor reported for semiconductor-based mechanical sensors to date. This gauge factor is approximately 30,000 times greater than that of commercial metal strain gauges and more than 2,000 times greater than that of cubic silicon carbide. The phenomenon discovered can pave the way for the development of ultra-sensitive sensor technology.
Discovered by Smith in 1954, the piezoresistive effect has been utilized as a major mechanical sensing technology. Piezoresistive sensitivity refers to the fractional change in resistance under applied strain, known as the gauge factor (GF). This sensing technology can be found in a wide range of applications, such as strain, force, pressure, and tactile sensors and accelerometers. The advantages of this sensing concept include, but are not limited to, low power consumption, simple readout circuits and miniaturization capability. However, the performance of the piezoresistive effect depends upon the carrier mobility, which is fundamentally limited by the nature of the piezoresistive materials.

The enhancement of the piezoresistive effect has been of great interest for developing ultra-sensitive sensing devices. The conventional strategy focuses on the arrangement of piezoresistors in optimal crystal orientations. For example, the longitudinal piezoresistive coefficient of p-type silicon (100) is ~6.6 × 10^11 Pa^-1 in the [100] direction, while its value increases to 71.8 × 10^11 Pa^-1 in the [110] direction. The GF of single crystalline p-type cubic silicon carbide (3C-SiC) is 5.0 and 30.3 in the [100] and [110] orientation, respectively. A significant improvement in piezoresistive sensitivity has also been demonstrated using optimal-doping concentrations. In terms of material choice, metal strain gauges have been commercialized and are widely employed in industry, research and daily life. However, the piezoresistive effect in metals is fundamentally based on a geometry change under applied strain, resulting in a low GF that is typically less than 2.

Semiconductors such as silicon (Si) and silicon carbide (SiC) have emerged as suitable materials for strain sensing because of their relatively high GF of up to 200 in Si and 30 in SiC. While the strain-induced geometry change can be neglected in these semiconductors, the carrier mobility governs the piezoresistive performance.

Interestingly, a significant enhancement of the piezoresistive effect can be achieved by scaling down piezoresistors to the nanometer-scale owing to advanced nanofabrication techniques. At the nanoscale level, the charge mobility and surface-to-volume ratio considerably increase, resulting in a significant improvement in the strain sensitivity. For instance, a large piezoresistive effect in top-down fabricated silicon nanowires (SiNWs) has been observed with a longitudinal piezoresistive coefficient of up to ~5500 × 10^11 Pa^-1, which is almost 38 times greater than that of bulk Si. However, the reliability of a large piezoresistive effect on the nanoscale is still controversial.

More recently, coupling piezoresistivity with other physical effects, such as piezoelectricity, has emerged as an advanced and promising approach to boost piezoresistivity. As such, the strain-modulated electric potential in piezoelectric materials, known as piezotronics, can be used to control or tune the transport of charge carriers. By utilizing strain-induced piezoelectric polarization charges at the local junction of zinc oxide (ZnO) nanowires to modify their energy band structures, Jun Zhou et al. successfully demonstrated an increase in the GF from 300 to 1250, when the strain increased from 0.2% to 1%. Additionally, an electrically controlled giant piezoresistive effect in SiNWs has been reported with a GF of up to 5000 by employing an electrical bias to manipulate the charge carrier concentration. Coupling of multiple physical effects in nanostructures has also been employed to modulate electrical transport in logic circuits, enhance the sensitivity and detection resolution of bio/chemical sensors, and improve the photovoltaic performance of solar cells.

In the present work, we report the discovery of a giant piezoresistive effect in semiconductor heterojunctions by coupling the photoexcitation of the charge carriers, the strain modification of the carrier mobility and the electric field modulation of the carrier energy. Visible light is utilized to illuminate the top layer material of the heterojunction structure, in which the sensing element is non-uniformly illuminated by a vertical visible light. This illumination generates a lateral photovoltage that is counteracted by an externally controlled electric field to tremendously modulate the magnitude of the piezoresistive effect. As a proof of principle, we employ a 3C-SiC nanofilm grown on a Si substrate to form a 3C-SiC/Si heterojunction. Under visible light illumination, a stable GF value of the SiC/Si heterojunction as high as ~58,000 is achieved, which is the highest value ever reported for semiconductor piezoresistive sensors. The piezoresistive effect in the SiC nanofilm is utilized to detect mechanical stress or strain, while its sensitivity is boosted by optimally and simultaneously regulating both the lateral photovoltage and the tuning current. While heavily doped p-type 3C-SiC/p-type Si (p^-3C-SiC/p-Si) is used in this work, our method could also be extended to enhance the sensitivity of other materials and smart structures that have simultaneous photovoltaic and piezoresistive properties. Thus, our findings can open a new era for the development of ultra-sensitive mechanical sensors.

Results

Enhancement of the piezoresistive effect. We demonstrated an unprecedentedly large piezoresistive effect in p^-3C-SiC/p-Si heterojunctions using a bending method. The carrier concentrations in the 3C-SiC nanofilm and Si substrate were 5 × 10^14 cm^-3 and 5 × 10^14 cm^-3, respectively. The light intensity was 19,000 lx, while three different strains of 225, 451, and 677 ppm were induced in the material (Fig. 1). In our experiments, we supplied an optimally controlled tuning current and simultaneously measured the output voltage.

We supplied a constant tuning current of 29.75 μA and light with an intensity of 19,000 lx. Strain was periodically applied (i.e., Load ON) and released (i.e., Load OFF). The fractional change in

![Fig. 1 The sensitivity enhancement by optoelectronic coupling. The piezoresistive effect in the cubic silicon carbide/silicon heterojunction was modulated by non-uniform visible light illumination on the surface of the sensing element coupled with an optimally controlled tuning current](image-url)
the resistance ($\Delta R/R_0$) was calculated as follows:

$$\Delta R = R - R_0 = \frac{V - V_0}{I} = \frac{V}{V_0} - 1$$

where the strain-free resistance $R_0$ is calculated by $R_0 = V_0/I$, $V_0$ is the voltage measured between the two electrodes under strain-free conditions, and $I$ is the supplied tuning current flowing between the two electrodes, which was kept constant throughout the measurement. When a strain or stress is applied, the resistance $R$ will change due to the piezoresistive effect. The value of resistance is calculated by $R = V/I$, where $V$ is the voltage measured between two electrodes under stress/strain application. As shown in Fig. 2a, b, the fractional changes in the resistance $\Delta R/R_0$ linearly increased with the increases in the tensile and compressive strain, which is desirable for high-performance strain-sensing applications. Figure 2c compares the fractional changes in the resistance $\Delta R/R_0$ between dark and light conditions under 451 ppm tensile strain, while Fig. 2d shows $\Delta R/R_0$ under 451 ppm compressive strain. Under a 451 ppm tensile strain, the $\Delta R/R_0$ value increased ~2950 times from 0.009 in the dark condition to 26.6 under light illumination, and this trend was similar under the compressive strain (the $\Delta R/R_0$ value increased from ~0.0087 to ~27 under the 451 ppm compressive strain). These results indicate a giant enhancement in the piezoresistive effect under light conditions. This tremendous enhancement was confirmed under other applied strains as well (Supplementary Fig. 1). The piezoresistive sensitivity is characterized by the GF, which is defined as the fractional resistance change in response to the applied strain:

$$\text{GF} = \frac{\Delta R}{R_0} \times \frac{1}{\varepsilon} = \frac{\Delta V}{V_0} \times \frac{1}{\varepsilon}$$

where $\varepsilon$ is the applied strain, which is detailed in Supplementary Table 1. Under the tensile strain, the GF was found to be 20 in the absence of light (the inset in Fig. 2a) and increased to ~58,000 under light illumination (Fig. 2a), which is the highest strain sensitivity ever reported. Moreover, under compressive strain, the change in the resistance or GF was similar to that observed under tensile strain but opposite in sign (Fig. 2b). In addition, the signal to noise ratio (SNR) under light condition increased significantly in comparison with that under dark condition.

**Tuning current in optoelectronic coupling.** The dependence of the piezoresistive effect on the tuning current under the 451 ppm tensile strain and the illumination condition of 19,000 lx intensity is depicted in Fig. 3. Figure 3a shows the change in the GF as the tuning current increased from 15 to 45 $\mu$A, while Fig. 3b–d illustrate the magnified graphs of the GF value versus the tuning current in three distinguished current ranges. The GF increased from approximately ~16 to ~1800 as the current increased from
15 to 29.45 \mu A (Fig. 3b), while it decreased from 1800 to ~50 for the high current ranging from 30 to 45 \mu A (Fig. 3d). This difference was attributed to the dominance of the photomodulated potential over the injected potential (i.e., tuning current). The compensation of these two potentials in the current range of from 29.45 to 30 \mu A led to a change in the GF sign and the ultra-high absolute GF values (Fig. 3c). As the strain-free voltage $V_0$ was relatively small due to the potential compensation, the modulation of the charge mobility under strain resulted in a significant change in the measured voltage, resulting in an ultra-high GF. It was observed that a higher GF can be achieved as the magnitude of the tuning current became closer to that of the photocurrent. For instance, under an incident light intensity of 19,000 lx, the maximum GF observed was as high as ~95,500. However, as the tuning current became closer to the photocurrent, the GF was more variable due to an inevitable slight variation in the photocurrent. Therefore, to achieve a higher stable sensitivity, the tuning current should be controlled and maintained as close as possible to the magnitude of the photocurrent but also far enough to retain stability. In our experiment, we achieved a stable GF of ~58,000 when the tuning current was help constant at 29.75 \mu A under an illumination of 19,000 lx from a stable visible light source.

As such, the significant enhancement in the piezoresistive effect by optoelectronic coupling in 3C-SiC/Si heterojunctions is a combination of two key elements: light illumination and tuning current. This enhancement was first attributed to the photogenerated electrical potential in the 3C-SiC film with non-uniform illumination of visible light, which was indicated by the lateral photovoltage and/or photocurrent. The magnitudes of the photovoltage and the photocurrent can be manipulated by parameters, such as light intensity, light position, or light wavelength. The lateral photovoltage, for example, was measured to be approximately ~9 mV under a light intensity of 19,000 lx (Fig. 4a), and the value of the photocurrent was ~29.7 \mu A (Fig. 4b). The magnitudes of the generated photovoltage and photocurrent can be changed by changing the light position. For instance, using the same previous light, we gradually adjusted the light beam position from the left (L) electrode to the right (R) electrode (Supplementary Fig. 2). The measured voltage decreased from a large positive value (e.g., 9 mV) at electrode L to zero at the center of the device and then increased to a large negative value at electrode R (e.g., ~9 mV). The underlying physics behind the generation of the photocurrent and photovoltage on 3C-SiC can be explained according to the lateral photovoltaic effect\[^{25}\]. Figure 5a shows the photon excitation of electron–hole pairs (EHPs) in the 3C-SiC/Si platform under light illumination. As such, photogenerated charge carriers have a high concentration at electrode R close to the light source. The formation of the gradient of charge carriers is discussed as follows.

**Formation of the gradient of charge carriers.** When heavily doped p-type 3C-SiC and p-type Si are brought together, holes diffuse from the 3C-SiC film into the Si substrate to decrease the hole gradient, leaving behind negative charges in the SiC layer near the interface of the heterojunction. In contrast, electrons in Si, as minor carriers, migrate into SiC and create a positive charge layer on the Si side. The migration of electrons and holes forms a depletion region (space charge region) and a built-in electric field $E_0$, which bends the conduction band and valence band in the

Fig. 3 The role of the tuning current in the enhancement of the piezoresistive effect. a Characteristics of GF with respect to the supplied tuning current. Three ranges of tuning current are magnified in b, the negative GF range; in c, the optimal range; and in d, the positive GF range. Under the same light condition, the sensitivity (i.e., GF) changed significantly versus the supplied current. Under a light intensity of 19,000 lx, as the supplied current was swept from 15 to 45 \mu A, the GF increased from approximately ~16 to a maximum of ~95,500, and then decreased to about ~50

\[^{25}\]
It is worth noting that the depletion region extends primarily into the Si substrate (Fig. 5a) because the carrier concentration in the Si substrate ($5 \times 10^{14} \text{ cm}^{-3}$) is much lower than that in the SiC thin film ($5 \times 10^{18} \text{ cm}^{-3}$). As shown in Fig. 5b, c, there are energy offsets of 0.45 and 1.7 eV for the conduction band and valence band, respectively, between 3C-SiC and Si. Figure 5b, c present the band energy diagrams of the heterojunction at the electrode L area without illumination b and at the electrode R area with illumination c. Under non-uniform illumination, photons are injected into the electrode R area rather than into the electrode L area, resulting in holes generated and injected in this area. Consequently, there is a gradient of the hole concentration in the 3C-SiC layer.

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tunneling mechanism. Under non-uniform illumination, the majority of photons migrated into the electrode R area rather than into the electrode L area, resulting in holes were injected into this area. Consequently, there was a potential gradient in the hole concentration from electrode R to electrode L, which resulted in a difference in the electric potential described as $V_{\text{ph}} = E_{\text{F,3C}} - E_{\text{F,L}}$, where $e$ is the elementary charge, $E_{\text{F,3C}}$ is the Fermi energy level, and $V_{\text{ph}}$ is the generated lateral photovoltage. When the external circuit was shorted, the only current in the circuit was the photocurrent ($I_{\text{photo}}$).

Hole redistribution. The potential gradient of the hole concentration from R to L can also be represented in the $E$–$k$ (energy–momentum) diagrams in Fig. 6. Under inhomogeneous illumination of light (Fig. 6a), the difference in the
photogenerated hole concentration at R and L resulted in a difference in the Fermi levels in the SiC thin film in the two electrode regions. When a bias current \( j \) with a positive terminal at electrode R and a negative terminal at electrode L is applied, the 3C-SiC band energy was bent upwards from electrode L to electrode R (Fig. 6b). This bias current created an electric field \( E_b \):

\[
E_b = \frac{\int_R^L j \cdot \frac{1}{\sigma} \, dx}{C_1 \sigma} \quad (3)
\]

where \( \sigma \) and \( x \) are the conductivity of SiC and the distance from electrode L, respectively. This electric field \( E_b \) offset the lateral photogenerated electric field \( E_{\text{ph}} = eV_{\text{ph}} \) resulting in a relatively small voltage \( V_0 \) between the two electrodes. Particularly, under a light intensity of 19,000 lx, a bias current of 29.75 \( \mu A \) almost canceled out the lateral photovoltage, resulting in a nearly zero voltage \( (V_0 \approx 0) \) (Fig. 6b). Figure 6c shows the change in the band diagram at the electrodes under uniaxial tensile strain. The energy sub-band of heavy holes (HHs) was shifted up to a lower energy level, while the energy sub-band of light holes (LHs) moved down to a higher energy level. As a consequence, there was an increase in the HH concentration and a decrease in the LH concentration, while the total concentration of holes was hypothesized to be unchanged due to the high doping concentration. It should be noted that as HHs have a higher effective mass than LHs, the increase in the HH concentration and the decrease in the LH concentration caused an increase in the total of the effective mass. Consequently, the mobility of the holes was reduced, which diminished the conductivity \( \sigma \) or increased resistance. As a result, the bias current generated a high electric field \( E \) and a high measured voltage \( V \). The significant difference between the
The tensile and compressive strains on the SiC devices were induced using a cantilever bending experiment. Three different weights of 50, 100, and 150 g were hung on the free end of the cantilever to induce strain in the sensing element. The strain calculation is detailed in Supplementary Note 1. We controlled the tuning electric current and simultaneously measured the voltage between the two electrodes using a Keithley 2450 SourceMeter.

**Data availability**

All relevant data of this work is available from the corresponding author upon reasonable request.

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Author contributions
T.N., T.D. and A.R.F. designed and carried out the experiments. T.D., H.-P.P. and T.-K.N. fabricated the samples. T.N. and T.D. analyzed the data. T.N., T.D., N.-T.N. and D.V.D. discussed the results. T.N., T.D. and D.V.D. co-wrote the paper. All authors commented on the manuscript.

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