Electronic Supplementary Information

Thickness dependence of piezoresistive effect in p-type single crystalline 3C-SiC nano thin film

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(1) Characterization of the current leakage through the SiC/Si heterojunction

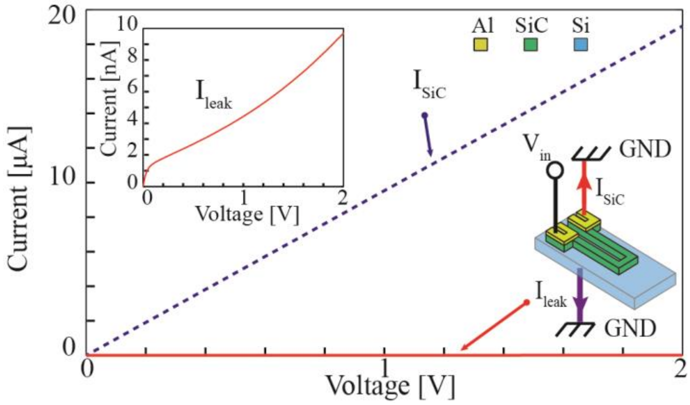

Fig.1 The IV curve of the SiC resistors and the current leakage through the SiC/Si heterojunction. Inset graph: The current leakage through the SiC/Si heterojunction plotted using different scale (nA).

The currents through the SiC resistor and the SiC/Si heterojunction were measured by sweeping the voltage of SiC with respect to Si (and the grounded electrode of the SiC resistor) from 0 to 0.5 V using an HP 4145B Analyzer. The IV curve of the SiC resistor shows good linearity, indicating the Ohmic contact between the metal (aluminium) and the SiC (Fig. 1 (a)). To avoid the Joule heating effect, the current applied to measure the resistance of SiC was set to be 1 μA, at which the ratio of the current leakage through the SiC/Si heterojunction to the current flowing through the SiC resistor was below 0.5% (Fig 1 inset).

(2) Simulation of bending experiment

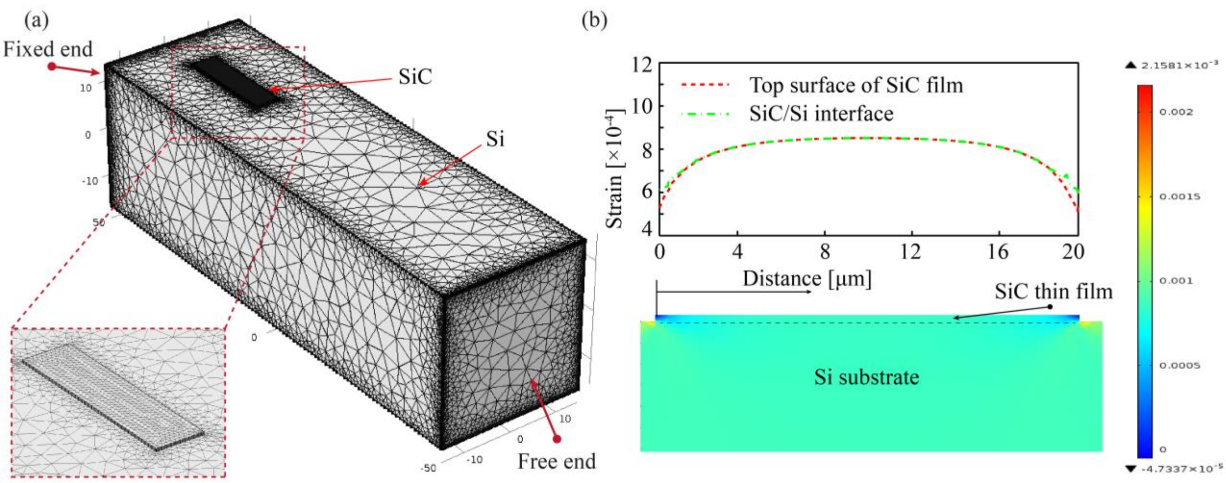

Fig.2 (a) The strain distribution in the SiC/Si beam. (b) Strain distribution along SiC resistor (upper part).

The simulation of the strain distribution in the 280 nm thin films is shown in Fig. 2. The results show that the strain in the Si layer was transmitted to the SiC layer with the ratio of over 98%. The strain was uniformly distributed along the SiC nano thin film. A smaller strain was observed at the top-edge of the SiC film. However as the length of this edge part is much smaller than the total length of the SiC resistor, therefore it is negligible.

The simulation was carried out with different thicknesses of the SiC films, which have the same trend as shown in Fig. 2. The average of the strain induced in the SiC resistor was used to calculate the gauge factor of the SiC thin films.

(3) Deduction and explanation for Eq. 2 and Eq. 4 of the manuscript

a. Equation 2

Let $\emptyset_{hd}$ and $\emptyset_{ld}$ are the sheet conductance of the high density defect layer and the low density defect layer, respectively.

From Eq. 1, the conductance of the SiC film (G_t) is

$$G_t = G_{hd} + G_{ld} = \emptyset_{hd}t_{hd} + \emptyset_{ld}t_{ld} = \emptyset_{hd}t_{hd} + \emptyset_{ld}(t_{SiC} - t_{hd}) \tag{S1}$$

Hence:

$$\frac{G_{hd}}{G_t} = \frac{\emptyset_{hd}t_{hd}}{\emptyset_{hd}t_{hd}+\emptyset_{ld}(t_{SiC}-t_{hd})} = f(t_{SiC}) \tag{S2}$$

All SiC films are grown under the same conditions; therefore the high density defect layers are expected to have the same thickness (t_{hd} = constant) and the same properties. Hence, $f(t_{SiC}) = \frac{G_{hd}}{G_t}$ is a monotonically decreasing function of the film thickness t_{SiC} and $f(t_{SiC})$ has a value between 0 and 1.

b. Equation 4

The gauge factor is defined as:

$$GF = \frac{1}{\varepsilon} \times \frac{\Delta R}{R} \tag{S3}$$

where R is the resistance of the SiC resistor; ε is the applied strain. The conductance of the SiC resistor is: $G = 1/R$. Therefore:

$$GF = \frac{1}{\varepsilon} \times \frac{\Delta R}{R} = \frac{1}{\varepsilon} \times \frac{R_2 - R_1}{R_1} = \frac{1}{\varepsilon} \times \frac{\frac{1}{G_2} - \frac{1}{G_1}}{\frac{1}{G_1}} = \frac{1}{\varepsilon} \times \frac{G_1 - G_2}{\varepsilon G_2} \approx -\frac{1}{\varepsilon} \times \frac{\Delta G}{G} \tag{S4}$$

Here, R_1 (or G_1) and R_2 (or G_2) are the resistance (or conductance) of the strain-free and strained SiC films, respectively.
Note that $G_t = G_{ld} + G_{hd}$ and $\Delta G_t = \Delta G_{ld} + \Delta G_{hd}$, hence Eq. (4) in the manuscript can be deduced by:

$$\begin{aligned} GF &= -\frac{1}{\varepsilon} \times \frac{\Delta G_{ld} + \Delta G_{hd}}{G_t} = -\frac{1}{\varepsilon} \times \frac{\Delta G_{ld}}{G_{ld}} \times \frac{G_{ld}}{G_t} - \frac{1}{\varepsilon} \times \frac{\Delta G_{hd}}{G_{hd}} \times \frac{G_{hd}}{G_t} \\ &= \frac{G_{ld}}{G_t} GF_{ld} + \frac{G_{hd}}{G_t} GF_{hd} = (1 - f(t_{SiC}))GF_{ld} + f(t_{SiC})GF_{hd} \end{aligned} \tag{S5}$$

where, GF_{ld} and GF_{hd} are the gauge factors of low density defect layer and high density defect layer, respectively.

$$\begin{cases} GF_{ld} = -\frac{1}{\varepsilon} \times \frac{\Delta G_{ld}}{G_{ld}} \\ GF_{hd} = -\frac{1}{\varepsilon} \times \frac{\Delta G_{hd}}{G_{hd}} \end{cases} \tag{S6}$$

(4) Estimation of the thickness dependence of the piezoresistive effect

From the TEM image, the thickness of the defect layer is about 60 nm (t_{hd} = 60 nm). As 60 nm is much smaller than 1 µm, the influence of crystal defect in 1 µm can be negligible. Therefore the gauge factor of the 1 µm film is approximately equal to that of the low density defect layer (GF_{ld} = 31.1).

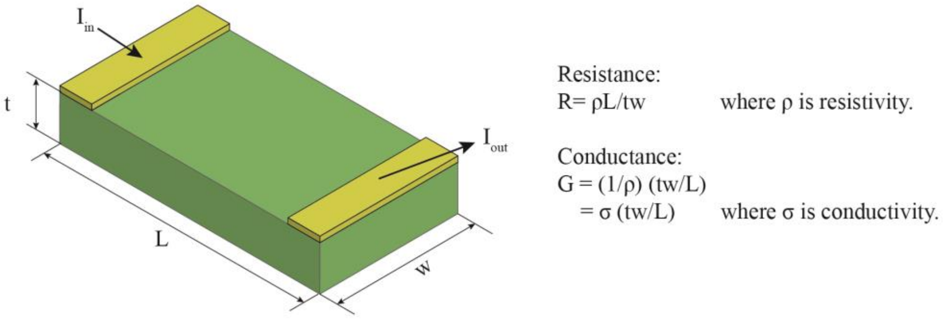

Fig. 3 Concept of the conductance of a SiC film

For a quantitative demonstration, we have compared the the 280 nm and the 80 nm. For other thicknesses, the same method can be applied. Let μ and σ be the carrier mobility and conductivity of the SiC film. The mobility of the 80 nm film and 280 nm film were measured to be approximately 7.5 cm^2/Vs and 15cm^2/Vs, respectively. Therefore : $\mu_{280} = 2\,\mu_{80}$
The conductivity of the SiC film is:

$$\sigma = n\mu q \tag{S7}$$

where n is carrier concentration, q is carrier charge. As these films have the same doping concentration, therefore $\sigma_{280} = 2\sigma_{80}$

The conductance of SiC film is:

$$G_t = \sigma \frac{wt}{L} \tag{S8}$$

Hence

$$\sigma_{280} = \frac{G_{280}}{280}\frac{L}{w} = 2\sigma_{80} = 2\frac{G_{80}}{80}\frac{L}{w} \tag{S9}$$

As the width and length of the films are the same, from Eq. (S9):

$$\frac{G_{280}}{280} = 2 \times \frac{G_{80}}{80} \tag{S10}$$

Substituting Eq. (S1) into Eq. (S10)

$$\frac{\emptyset_{hd}60+\emptyset_{ld}(280-60)}{280} = 2 \times \frac{\emptyset_{hd}60+\emptyset_{ld}(80-60)}{80} \tag{S11}$$

Hence, the ratio of the sheet conductance of the high density defect layer and the low density defect layer has been calculated as:

$$\frac{\emptyset_{hd}}{\emptyset_{ld}} = \frac{1}{4.5}$$

Substituting this value into Eq. (S2):

$$f(t_{SiC}) = \frac{t_{hd}}{t_{hd}+4.5(t_{SiC}-t_{hd})} = \frac{60}{60+4.5(t_{SiC}-60)} \tag{S12}$$

Substituting Eq. (S12) into Eq. (S5), from the measured gauge factor of the 80 nm film, the gauge factor of the high density defect layer was calculated as GF_{hd} = 4.1. From the values of GF_{hd} and GF_{ld}, the estimated gauge factors of 3C-SiC films are listed in Table A.

Table A: Comparison between estimated GF and measured GF

Thickness	Measured	Estimated
80 nm	20.5	20.5
130 nm	26.1	26.9
280 nm	30.3	29.6
380 nm	30.4	30.0
1000 nm	31.1	30.5

List of symbols:

G_t	The total conductance of the SiC film
G_{hd}	The conductance of the high density defect layer of the SiC film
G_{ld}	The conductance of the low density defect layer of the SiC film
GF	The gauge factor of the SiC films
GF_{ld}	The gauge factor of the low density defect layer of the SiC film
GF_{hd}	The gauge factor of the high density defect layer of the SiC film
μ	The carrier mobility of the SiC film
σ	The conductivity of the SiC film
Φ	The sheet conductance of the SiC film
Φ_{hd}	The sheet conductance of high density defect layer of the SiC film
Φ_{ld}	The sheet conductance of low density defect layer of the SiC film
t_{SiC}	The thickness of the SiC film
t_{hd}	The thickness of the high density defect layer of the SiC film
t_{ld}	The thickness of the low density defect layer of the SiC film
L	The length of the SiC resistor
w	The width of the SiC resistor