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Piezoresistive effect of n-type \(\langle 111\rangle\)-oriented Si nanowires under large tension/compression

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Abstract
Small-scale samples enable us to understand changes in physical properties under larger strain due to their higher tolerance to deformation. In this study, the piezoresistive character of n-type \(\langle 111\rangle\)-oriented Si nanowires under large strain was measured during tensile and compressive deformations. The Si nanowires were directly cut from the wafer using top-down technology and deformed while capturing their electrical properties inside a transmission electron microscope. The experimental results show that both tensile and compressive deformation enhanced their electrical transport properties. The piezoresistance coefficient is of the same order of magnitude as its bulk counterpart, but half as large, which may be attributed to a larger strain magnitude. We also studied the circulatory characteristics and influence of electron beam radiation. This study provided new physical insights into piezoresistive effects under large strain.

Keywords: silicon piezoresistance, tensile strain, compressive strain

Some figures may appear in colour only in the online journal

Introduction
Silicon is widely used as a fundamental material in the electronics industry, due to its stable performance and mature processing technology. Since the piezoresistive effect (PRE) of silicon was first reported in 1954 [1], strain-induced semiconductor property modulation has been observed and has been successfully used in pressure sensors based on the relationship between the change in resistance and applied stress (strain). However, this relationship was built based on a very low strain magnitude due to the brittleness of bulk Si and is only adapted to small strains of less than 0.1% [2]. Matsuda \(et\ al\) reported the nonlinearity of PRE in Si due to a third-order effect [3, 4]. Chen \(et\ al\) measured the PRE of a 150 nm-diameter single-crystal Si fibre under 1% tensile strain and found that second- and third-order effects should not be ignored when the strain is greater than 0.1% [5]. Thus, the piezoresistive effect should be recognized in small-scale semiconductors for improved applications because they can exhibit much higher deformation capability than their bulk counterparts [6–11]. The magnitude of elastic strain for Si nanowires is reportedly up to 10% [10–13].

Many experimental studies in the past decade have focused on the PRE of small-scale n/p-type Si with \(\langle 111\rangle\), \(\langle 110\rangle\), and \(\langle 100\rangle\) orientations [14–29]. However, the results are different, even paradoxical, which may result from the effects of external factors. For example, Yang \(et\ al\) reported a giant piezoresistance coefficient (PRC) in p-type \(\langle 111\rangle\) and \(\langle 110\rangle\)-oriented silicon nanowires, which was approximately 37 times greater than that of the bulk value [14]. However, Milne \(et\ al\) found that this giant PRE resulted from electron
and hole trapping at the sample surfaces and the true PRE was similar to that of the bulk form [15]. For n-type (111)-oriented silicon nanowires, the reported results also exhibit a discrepancy. Zhang et al achieved the uniaxial tension process for chemical vapour deposition (CVD)-grown silicon nanowires, and found that the resistance was reduced by a factor of 26.8 (gaug factor, strain sensitivity) compared with the resistance at zero strain using a microelectromechanical system (MEMS) device in a scanning electron microscope (SEM) [16]. Bernal et al, on the other hand, obtained a much lower piezoresistance effect using another type of MEMS; they measured the PRC of a stretched silicon nanowire prepared using a low-pressure chemical vapour deposition method (LPCVD) in a SEM, and found that the PRC was −2.1 to −3.7 × 10⁻¹¹ Pa⁻¹, similar to that of the bulk form [17]. Megan et al studied the piezoresistive characterization of silicon micro-wires (prepared using the CVD method) under bending deformation and found that the PRC was within an order of magnitude of bulk n-type silicon and was related to the doping concentrations [18]. Under bending conditions similarly, Obi et al found that pulsed laser deposition (PLD)-prepared silicon nanowires had a gauge factor up to 600 [19]. The discrepancy of these experimental results may result from the doping level, structural quality, or strain state. Compared with top-down preparation technology, it is difficult to control the doping level accurately with bottom-up preparation technology. Thus, it is necessary to obtain systematic measurements based on Si nanowires prepared using top-down technology. Furthermore, to the best of our knowledge, there are no reports on the effects of compressive strain changes on the electrical properties of n-type (111)-oriented silicon nanowire.

In this study, n-type (111)-oriented silicon nanowires were prepared using a focused ion beam technique from n-type silicon wafer. Tensile and compressive stresses were applied to individual silicon nanowires along the axial direction, and their corresponding electrical responses were simultaneously captured inside a transmission electron microscope. Based on these measurements, the piezoresistive characteristics of n-type (111)-oriented silicon nanowires were obtained under tension and compression.

Experimental

Experimental method

A commercial scanning tunnelling microscope-transmission electron microscope (STM-TEM) joint instrument (Nanofactory TM), inserted into a TEM, was used to manipulate nanomaterials. Figure 1 shows a schematic illustration of the experimental setup and process. Figure 1(a) shows a schematic diagram of the STM-TEM probing system. A movable tungsten probe connected to a piezo-tube is used for two functions: probing and the electrode. The target sample is placed on a silver wire by deposited platinum using a focused ion beam (FIB). Figure 1(b) is an enlarged schematic diagram of the area enclosed by the dashed rectangle in figure 1(a). By precisely controlling the movement of the tungsten probe in three dimensions with the piezo-tube (driven by the STM-TEM probing system), NWs can be contacted and deformed, as illustrated in figure 1(c). During this deformation process, I–V curves can be measured and recorded simultaneously. To achieve the stretching process and a good contact, electron beam-induced deposition (EBID) technology was used to bond the sample and tungsten probe (shown in figure 1(c)). Additional details can be found in references [30–34].

Sample preparation

A dual-beam system (FEI Helios-600i) was employed to prepare (111)-oriented Si nanowires that were cut from a silicon single-crystal wafer (with a flat and clean (111) surface). This wafer was doped with phosphorus, and its electrical resistivity was 1–10 Ω cm. A schematic drawing shows the TEM sample preparation process in figure 2(a). First, a Si slice perpendicular to the wafer was formed using FIB. Prior to this step, platinum (Pt) was deposited on the Si surface to form a protective layer to avoid damage to the sample. Second, a tungsten probe was precisely controlled to approach and fix the slice by deposition of Pt. Then, the slice was cut and lifted from the wafer. The slice was transferred onto a silver wire, fixed together and cut from the probe tip. Finally, the Si slice was thinned to approximately 200 nm, and several Si nanowires were prepared using a weak ion beam, under 2 keV, to reduce damage.

Figure 2(b) provides a low-magnification TEM image showing several nanowires cut from a Si (111) wafer. The prepared nanowires have different diameters, for performing stretched or compressed deformation. The diameters range from 100 nm to 300 nm. Figure 2(c) shows the corresponding
selected area electron diffraction (SAED) pattern along the zone-axis of (112) taken from the blue circled region in figure 2(b), from which we can confirm that the nanowire is a single crystalline structure and the longitudinal direction is (111).

Results

Tensile deformation and corresponding electrical measurements

Using the STM-TEM probing system, *in situ* deformation processes and electrical measurements were carried out in the TEM. Figure 3 shows a series of TEM images of a tensile nanowire demonstrating different strain states. To perform a tensile process, EBID was first used to weld the nanowire and tungsten probe, as indicated by the yellow arrow in figure 3. Using Gatan DigitalMicrograph software (version 2.10.1282), the length variations were measured accurately and the corresponding strains calculated using the following formula:

\[ \varepsilon = \frac{l - l_0}{l_0} \]  

where \( l_0 \) is the initial length and \( l \) is the final length.

From the TEM images, we measured the lengths of each state to be 2.496 \( \mu m \) (state 1), 2.512 \( \mu m \) (state 2), 2.533 \( \mu m \) (state 3), 2.542 \( \mu m \) (state 4), 2.553 \( \mu m \) (state 5) and 2.57 \( \mu m \) (state 6). The tensile strain in these states was 0.64%, 1.48%, 1.84%, 2.28%, and 2.96% respectively. Finally, the tungsten probe was fractured (state 7), and the nanowire fully recovered to its initial length.

Simultaneously, the electrical property of each state was measured using the same probing system during the tensile process. Figure 4(a) shows seven \( I-V \) curves taken from each state of figure 3. Voltages from −3 V to 3 V were applied to the Si nanowire. The \( I-V \) curves were not linear for the whole range, which means that Schottky barriers existed in the structure of tungsten–silicon–silver. So we chose the linear part of \( I-V \) curve under large voltage (2–3 V) to calculate the resistance of the nanowire [35, 36], and the relative change in resistance (\( \Delta R/R_0 \)) in the nanowire can be obtained. Figure 3(b) shows the relationship between the relative change in resistance and tensile strains, from which it is clear that the relative resistance reduces with increasing tensile strain and a nearly linear relationship can be fitted up to 3% tensile strain.

To show the change sensitivity of resistance versus strain, the gauge factor (GF) [37] is defined as:

\[ GF = \frac{\Delta R/R_0}{\varepsilon} \]  

where \( \varepsilon \) is the strain and \( \Delta R/R_0 \) is the fractional resistance change with strain. The gauge factor of the tensile Si nanowire was calculated to be approximately −5.59. The
Similarly, we studied the electrical properties of n-type Compressive deformation and corresponding electrical longitudinal piezoresistance coefficient $\pi_1$ was obtained for the relation between GF and $\pi_1$ [37]:

$$ \text{GF} = Y_1\pi_1 $$

where $Y_1$ is Young’s modulus (169 GPa for bulk silicon along the (111) direction [38]). The piezoresistance coefficient of the tensile Si nanowire was calculated to be approximately $-3.3 \times 10^{-11} \text{Pa}^{-1}$ (we only discuss the first-order piezoresistance coefficient $\pi_1$ here). Compared with Bernal’s results [17] for the n-type (111)-direction Si nanowire, our result is similar. In their results, the coefficient was $-2.1 \times 10^{-11} \text{Pa}^{-1}$ for a 114 nm-diameter nanowire and $-3.7 \times 10^{-11} \text{Pa}^{-1}$ for a 141 nm-diameter nanowire.

**Compressive deformation and corresponding electrical measurements**

Similarly, we studied the electrical properties of n-type (111)-oriented Si nanowires under compressive strain. As the tungsten probe moved forward, compressive deformation occurred on a Si nanowire. Figure 5(a) shows six deformed TEM images, from which we can see that obvious bending occurred when applying larger deformation (states 4–6). Unlike tensile deformation, compression may easily induce bending or buckling deformations in a one-dimensional structure. To reduce these phenomena, a nanowire with a small length:diameter ratio ($\sim 3$) was used in this compressive deformation. The emergence of a bending phenomenon could have resulted from the non-uniaxial press. Due to the bending deformation, the strain distributions were complicated. To better understand the strain, finite element analysis was employed to simulate the distribution of each deformed state, with the assumption of fully elastic deformation. Figure 5(b) shows the corresponding maximum principal (absolute) strain distributions of each state in figure 5(a). From them, we can see that state 2 and state 3 nearly suffered from compressive strain. Thus, the corresponding strains were $-1.04\%$ and $-2.12\%$ respectively, according to length variations from $1.077 \mu m$ (initial length) to $1.066 \mu m$ (state 2) and $1.055 \mu m$ (state 3). However, the strains presented a gradient distribution along a radial direction for states 4–6. For state 4, the strain gradients were from $-4.76\%$ to $-7.62\%$. Thus, an average strain of $\sim-6.19\%$ was obtained, which could also be reflected from the yellow region. For state 5, the gradients were from $-5.11\%$ to $-8.57\%$ and an average strain $\sim-7.14\%$ was obtained. This is reflected by the orange region. For state 6, the gradients were distributed from $-6.67\%$ to $-9.52\%$ and an average strain of $\sim-8.09\%$ was obtained (red region in state 6).

Along with the deformations, the electrical properties of the strained Si nanowire were measured. Figure 6(a) shows the corresponding $I$–$V$ curves of each deformed state. Linear $I$–$V$ curves were obtained, indicating that good ohmic contact between the Si and the electrode was achieved. The slope of an $I$–$V$ curve represents the conductivity of the nanowire, and we can see that the conductivity of the Si nanowire was improved with increasing compressive strain. A similar trend has been reported in the bending process for Si micro-wires [18].

It is well known that $R$ (resistance) is the ration of $U$ (voltage) to $I$ (current). Thus, the following relationship can be deduced:

$$ \Delta R/R_0 = -\Delta I/I $$

where $I$ is the final current, $R_0$ is the initial resistance, and $\Delta R = R - R_0$ ($R$ being the final resistance).

Based on these $I$–$V$ curves, we calculated the relative resistance changes ($\Delta R/R_0$), and figure 6(b) shows the relationship between $\Delta R/R_0$ and strain. When the strain is less than $2\%$, a nearly linear relationship can be observed, but with higher strain, a nonlinear variation is obviously exhibited. We chose the linear data from the low-strain (<2.0%) states, and calculated the gauge factor to be approximately $3.27$ and the piezoresistance coefficient to be $\pi_1 = 1.9 \times 10^{-11} \text{Pa}^{-1}$.

**Circulatory characteristics under compressive strain**

To investigate the circulatory properties of the strained Si nanowire, we performed another experiment. We kept a 1 V
bias voltage for the closed circuit to detect current variations during the strain loading or unloading processes. As one circulation, we moved the tungsten tip forward two steps to apply compressive strains (10 nm per step) and backward two steps to release the strains. Figure 7 shows three complete circulations, reflecting the relationship between the current and time. We can see that 5 stages were included in a circulation. Each stage took 30 s. The average current was 368 nA, 377.5 nA, 388 nA, 377.5 nA and 368 nA for stages 1–5 respectively. These results indicate that the Si nanowire is highly reproducible and has good stability in terms of stress-induced change in the electrical properties.

Electron beam radiation effect on electrical transport

It has been reported that electron beam radiation can affect electrical transport properties [16, 39]. To study the influence of the radiation on the transport properties during the strain loading process, we carried out two series of experiments—one with electron beam irradiation and the other without it—during an identical compressive process for a Si nanowire. Figure 8 shows the relationship between the current and applied strain for a Si nanowire. The square and triangle curves represent current variations with strain, respectively with and without electron beam irradiation. Comparing the two curves, we can conclude that electron beam irradiation would enhance the electrical transport property of the Si nanowire, but would not change the tendency of current growth caused by strain. The incremental values remained almost constant.

Discussion

We noted that our piezoresistance coefficient for n-type \langle 111 \rangle-oriented Si nanowire was $-3.3 \times 10^{-11} \text{ Pa}^{-1}$, which is the same order of magnitude as its bulk counterpart, but much smaller ($-7.53 \times 10^{-11} \text{ Pa}^{-1}$) [37]. We also noted that our piezoresistance coefficient is in accordance with that reported by Bernal et al [17], although the measurement system was different and their nanowires were prepared using the bottom-up method (chemical vapour deposition). We considered the following factors in this issue: doping concentration, size effect and strain magnitude.

The doping concentration determines the resistance, and has a non-ignorable influence on the PRC [37]. In our case, the electrical resistivity of the sample is $\sim 10 \Omega \text{ cm}$, similar to that in reference [37]. This indicates that this discrepancy should not be a result of the influence of doping concentration. The size effect is considered because, compared our study and Bernal’s [17] with Kanda’s (bulk Si) [37], the sizes...
of the samples were obviously different. In our study and Bernal’s, the size (diameter/width/thickness) of the Si was ∼100–200 nm. It is reported that the surface effects, such as different surface states [14, 22], crystallographic properties [24] and charge trapings [15], would enhance the piezo-resistance effect rather than weaken it. Thus, the discrepancy should not be attributed to surface effects.

Another factor is the difference in magnitudes of applied strain. For measurements in bulk Si, the applied strain is very limited, usually from 0.01% to 0.1%. Thus, the piezo-resistance coefficient obtained in bulk is determined from very low strain. However, for nano-scaled Si, it is difficult to distinguish such a small strain or the electrical signal induced by it. Usually, the magnitude of the detected strain is larger than 0.1%. Hence, the PRC at nanoscale usually corresponds to a larger magnitude of strain. A previous work reported a nonlinear phenomenon of piezoresistance in sub-micron diameter Si fibre when the strain ranged from 0.1% to 1% and the piezoresistance coefficient decreased at high strain levels [5]. Based on this information, we considered that the discrepancy in comparison with bulk Si could result from the applied strain magnitudes.

Because the piezoresistance coefficient of a n-doped ⟨111⟩ Si nanowire is very small, the contributions of dimensional changes and the change in resistivity for the change of relative resistance should be reconsidered. It is well known that the change in relative resistance of semiconductors induced by strain is attributed to dimensional changes and the change in resistivity (resulting from the change in band structure). The relative resistance can be expressed as [37]:

$$\frac{\Delta R}{R_0}/\varepsilon = 1 + 2\nu + \frac{\Delta \rho/\rho_0}{\rho} \varepsilon$$

where $\varepsilon$ is the strain, $\rho$ is the resistivity and $\nu$ is the Poisson ratio (0.18 for silicon with uniaxial strain along the ⟨111⟩ direction [40]). The first two terms in the above equation represent the change in resistance due to dimensional changes, and the last term represents the change in resistivity. For bulk silicon, the dimensional gauge can be ignored because the resistivity change is larger than the dimensional change by a factor of approximately 50 [37]. However, we found that the change of resistance induced by dimensional change cannot
be ignored. For tension, the GF is $-5.59$, and thus, $(\Delta \rho / \rho_0) / \varepsilon$ is $-6.95$. For compression, the GF is $3.27$, and thus, $(\Delta \rho / \rho_0) / \varepsilon$ is $1.91$. The resistivity change is nearly the same as the dimensional change, which indicates that the band structure variations are not sensitive to strain for n-type $(111)$-oriented Si.

**Conclusion**

In summary, we prepared n-type $(111)$-oriented Si nanowires from wafers using the focused ion beam technique and investigated the piezoresistive effect of the Si nanowires using an in situ STM-TEM probing system. After establishing a reliable contact via EBID, large deformations and corresponding electrical measurements were achieved simultaneously. The resistance of the Si nanowires was reduced continuously in both tensile and compressive processes, and the measured piezoresistance coefficient was of the same order of magnitude as its bulk counterpart, but smaller: $-3.3 \times 10^{-11}$ Pa$^{-1}$ and $1.9 \times 10^{-11}$ Pa$^{-1}$ for tension and compression respectively. We also studied the influence of an electron beam on transport properties during the strain loading process and found that the electron beam did not change the tendency of current growth caused by strain.

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