Characteristics of Polycrystalline Si Nano Wire Piezoresistors

Student Member  Yasutada Tanimoto (Ritsumeikan University)
Member           Toshiyuki Toriyama (New Energy and Industrial Technology Development Organization)
Member           Susumu Sugiyama (Ritsumeikan University)

Summary

This paper describes the first study on a polycrystalline Si (poly-Si) nano wire from the viewpoint of MEMS mechanical sensor application. In order to confirm an ability of the poly-Si nano wire piezoresistor as a sensing element of a mechanical sensor, current-voltage (I-V) characteristics and the piezoresistive effect were investigated. The poly-Si nano wire piezoresistor, whose thickness is 32nm and width is 53nm, was fabricated by the combination of the electron beam (EB) direct writing and RIE. A remarkable phenomenon was observed. The longitudinal piezoresistive coefficient $\pi_L$ of the nano wire piezoresistor increased with a decrease in the cross section area, while the transverse piezoresistive coefficient $\pi_T$ was approximately zero and invariant despite variation of the cross section area. The maximum value of the longitudinal piezoresistive coefficient $\pi_L$ of the nano wire piezoresistor was $22 \times 10^{-5}$ (1/MPa) at impurity concentration $N = 5 \times 10^{19}$ (cm$^{-3}$).

Keywords: piezoresistive effect, nano wire, poly-Si, EB direct writing

1 INTRODUCTION

MEMS have progressed from micro to nano scale with the aid of advanced semiconductor process technology. As a consequence, it is expected that novel MEMS will be developed by applying functions of nano order semiconductor structures (1),(2).

In the field of electronics, the fabrication process and characteristics of nano order semiconductor structures, such as quantum dots and quantum nano wires, have been widely investigated in order to develop quantum electronics devices (3),(4). Nevertheless, applications of functions of nano order semiconductor structures to MEMS have been just begun and several papers concerning the above topics have been published (1),(2).

In this paper, the nano wire has been studied from the viewpoint of a mechanical sensor application. Polycrystalline silicon (poly-Si) nano wire piezoresistors were fabricated by the electron beam (EB) direct writing and RIE processes. Electrical and electromechanical (piezoresistive effect) characteristics of the poly-Si nano wire piezoresistors were investigated in order to verify abilities as sensing elements of mechanical sensors. A remarkable phenomenon has been observed. The longitudinal piezoresistive coefficient of the poly-Si nano wire piezoresistor increased with a decrease in the cross section area. A validity of the poly-Si nano wire piezoresistor for mechanical sensor application and a qualitative physical interpretation of observed phenomenon have been discussed.

2 PIEZORESISTIVE EFFECT

The piezoresistive effect is interpreted as a resistance change in a solid due to applied stress. When biaxial normal stresses are applied to a piezoresistor as shown in Fig.1, the piezoresistive effect can be expressed as follows (6):

$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$$

(1)

Where $\Delta R/R$ is the resistance change ratio due to applied stress, $\sigma_L$ is longitudinal normal stress whose direction is parallel to electrical field $E$ and current density $J$, and $\sigma_T$ is transverse normal stress whose direction is perpendicular to $E$ and $J$. $\pi_L$ and $\pi_T$ are longitudinal and transverse piezoresistive coefficients, respectively.

![Fig.1 Piezoresistor subjected to biaxial normal stresses.](image-url)
3 FABRICATION PROCESS OF POLY-Si PIEZORESISTORS

Figure 2 shows the fabrication process of the poly-Si piezoresistors. Nano wire structure of the piezoresistor can be realized by using the EB direct writing and RIE processes.

(a) A SiO₂ insulation layer 0.7 μm - thick was deposited on an n-type Si (100) substrate by thermal oxidation. p-type poly-Si layer 0.5 μm - thick was deposited on the SiO₂ layer by LPCVD. Impurity concentration N of the poly-Si layer was controlled by boron ion implantation. N = 5 × 10¹⁹ (cm⁻³) was prepared (sheet resistance = 141.7 Ω/□).

(b) By using the EB lithography system, patterns of the piezoresistors were directly written onto the EB resist, which was spun on the poly-Si layer.

(c) The piezoresistors were fabricated by SF₆ RIE, where EB resist was used as an etching mask.

(d) Electrodes were fabricated by Al vacuum evaporation and photolithography. Finally, sintering was done in dry N₂ at 450°C for 30 min.

4 CHARACTERISTICS OF POLY-Si NANO WIRE PIEZORESISTORS

Table 1 summarizes the dimension and resistance of the fabricated nano wire piezoresistors. The nano wire piezoresistors have triangular or trapezoidal cross sections. Here, aspect ratio is defined as a ratio of (thickness)/(mean width) the nano wire piezoresistor. The aspect ratio is within the range from 0.15 to 1.26 as shown in Table 1. The calculated resistance values are obtained from geometry of the nano wire piezoresistors and sheet resistance of the poly-Si layer (sheet resistance = 141.7 Ω/□). Experimental resistance values are in good agreement with calculated values except for nano wire piezoresistor of No.5. Figure 3 shows an SEM micrograph of grains and grain boundaries of the LPCVD deposited poly-Si layer. Average grain size is approximately 100nm. Width and thickness of the nano wire piezoresistor No.5, whose cross section area is the smallest among the five piezoresistors, are less than one-grain size. Figure 4 shows an SEM micrograph of the fabricated nano wire piezoresistor.

Table 1 Dimension and resistance of the fabricated nano wire piezoresistors.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Thickness</th>
<th>Width</th>
<th>Length</th>
<th>Cross section</th>
<th>Aspect</th>
<th>Resistance(kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(μm)</td>
<td>(μm)</td>
<td>(μm)</td>
<td>(μm^2)</td>
<td>ratio</td>
<td>calculation</td>
</tr>
<tr>
<td>1</td>
<td>0.547</td>
<td>3.591</td>
<td>3.74</td>
<td>3.88</td>
<td>0.15</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>0.547</td>
<td>0.591</td>
<td>0.74</td>
<td>0.88</td>
<td>0.74</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>0.196</td>
<td>0</td>
<td>0.16</td>
<td>0.312</td>
<td>1.26</td>
<td>15.2</td>
</tr>
<tr>
<td>4</td>
<td>0.108</td>
<td>0</td>
<td>0.13</td>
<td>0.263</td>
<td>0.82</td>
<td>32.7</td>
</tr>
<tr>
<td>5</td>
<td>0.032</td>
<td>0</td>
<td>0.053</td>
<td>0.105</td>
<td>0.61</td>
<td>277</td>
</tr>
</tbody>
</table>

Fig. 2 Fabrication process of poly-Si piezoresistors.

Fig. 3 SEM micrograph of grains and grain boundaries.

Fig. 4 SEM micrograph of the fabricated nano wire piezoresistor (width = 53 nm, thickness = 32 nm).
Figure 5 shows current-voltage (I-V) characteristics of the nano wire piezoresistor under room temperature. The I-V characteristics of the nano wire piezoresistor have a linear relation and metal-semiconductor contact has a negligible resistance regardless of the polarity of the applied voltage (7). Thus, ohmic contact is realized.

Figure 6 shows resistance change in the nano wire piezoresistor due to applied stress under room temperature. A linear relation between the resistance change ratio and the applied stress is obtained. The stress was applied to the piezoresistors by using a simple cantilever system. The cantilevers were prepared by dicing a Si (100) substrate into rectangular strips, on which the piezoresistors were fabricated and whose longitudinal directions were along [011]. Then, stress level of the cantilever is easily calculated from the elementary elasticity. It is assumed that strains on the Si (100) substrate are completely transmitted into the piezoresistors. Validity of this assumption will be discussed in the following section. From this assumption, stresses in the piezoresistors are calculated through Hooke’s law:

\[ \sigma = E_{\text{poly-Si}} \varepsilon \]  (2)

Where \( E_{\text{poly-Si}} \) is the Young’s modulus of poly-Si and \( E_{\text{poly-Si}} = 170 \text{GPa} \) (8).

Figure 7 shows arrangements of the piezoresistors against crystallographic orientations of Si (100) substrate and direction of the applied stress. The piezoresistive coefficients \( \pi_i \) and \( \pi_s \) were calculated by means of these arrangements, equations (1) and (2).

Figure 8 shows the relation between the piezoresistive coefficients \( \pi_i \) and \( \pi_s \), and the cross section area of the piezoresistors. The longitudinal piezoresistive coefficient \( \pi_i \) of the nano wire piezoresistor increased with a decrease in the cross section area, while the transverse piezoresistive coefficient \( \pi_s \) was approximately zero and invariant despite variation of the cross section area. An interpretation of this phenomenon will be discussed in the following section.

5 DISCUSSION

As can be seen from Table 1, the experimental resistance value is about five times larger than calculation for nano wire piezoresistor of No.5. This result suggests that resistivity of nano wire piezoresistor of No.5 increased comparing to the others. This might be due to a surface depletion layer in which carriers are trapped (10). The surface depletion layer is induced on free surface of the nano wire piezoresistor during RIE.

One possibility to interpret the increase in the \( \pi_i \) is resistivity enhancement phenomenon. The five times enhancement of the resistivity from initial value corresponds to approximately 18% increment of \( \pi_i \) for the
conventional $p$-type poly-Si piezoresistors $^{13(16)}$. As can be seen from Fig.8, the maximum increment of the $\pi_t$ is approximately 30% with the decrease in the cross section area and higher than this. Therefore, the increment of the $\pi_t$ cannot be interpreted by resistivity enhancement alone. Another possibility for interpretation might be due to one-dimensional carrier transport, which is induced by the nano wire structure $^{(9)}$. Further investigation of the piezoresistance based on a valence band for one-dimensional case remains as a future work. Mean distance between carriers is approximately 3nm at $N = 5 \times 10^{19}$ (cm$^{-2}$). Thus, pure one-dimensional wire might be realized in the case where width and thickness of the wire are approximately 3nm. Therefore, condition of the fabricated nano wire piezoresistor is different from the pure one-dimensional case and corresponding to quasi-one-dimensional case.

Figure 9 shows an FEM analysis model and Fig.10 shows the result of FEM stress analysis for the nano wire piezoresistor. The substrate, on which the nano wire piezoresistor is arranged, is composed of a Si and a SiO$_2$ layer as previously mentioned in the fabrication process. The substrate is subjected to a normal stress $\sigma$ whose direction is perpendicular to the longitudinal direction of the nano wire piezoresistor. A stress gradient in the transverse normal stress $\sigma_t$ through the thickness is induced into the nano wire piezoresistor. While, $\sigma_t$ is almost invariant through the width and length. An average of the transverse normal stress $\sigma_t$ through the transverse cross section area can be estimated by

$$\sigma_t = \frac{\int \sigma_t \, dA}{\int dA}$$

(3)

Where $dA$ is a small element in the transverse cross section area of the nano wire piezoresistor. From the result in Fig.9 and equation (3), $\sigma_t \sim \sigma/5$ is obtained. Therefore, transverse normal stress $\sigma_t$ is not efficiently transmitted from the substrate into the nano wire piezoresistor. This is reason why the apparent transverse piezoresistive coefficient $\pi_t$ was relatively small.

Maximum value of the longitudinal piezoresistive coefficient $\pi_t$ of the nano wire piezoresistor is $22 \times 10^{-4}$ (1/MPa) at $N = 5 \times 10^{19}$ (cm$^{-2}$) and this value has enough sensitivity for mechanical sensor application.

Table 2 shows comparison of the piezoresistive coefficients $\pi_t$ and $\pi$ of conventional $p$-type poly-Si piezoresistors with the present poly-Si nano wire piezoresistor. The $\pi_t$ and $\pi$ of conventional $p$-type poly-Si piezoresistors are obtained from the gauge factors $G$ by multiplying $E_{\text{poly-Si}} = 170\text{GPa}$ to $G$ $^{(17)}$. As can be seen from Table 2, the present $\pi_t$ is larger than values for conventional piezoresistors at $N = 5 \times 10^{19}$ (cm$^{-2}$).
Table 2 Comparison of piezoresistive coefficients for conventional \( p \)-type poly-Si piezoresistors.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Longitudinal piezoresistive coefficient ( \pi_l (\times 10^{19} \text{MPa}^{-1}) )</th>
<th>Transverse piezoresistive coefficient ( \pi_t (\times 10^{19} \text{MPa}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germer and Todt [11]</td>
<td>1.7 ( \times 10^{19} )</td>
<td>Not available</td>
</tr>
<tr>
<td>P.J. French and Evans [12]</td>
<td>2.2 ( \times 10^{19} )</td>
<td>Not available</td>
</tr>
<tr>
<td>M. Le Berre et al [13]</td>
<td>2.0 ( \times 10^{19} )</td>
<td>Not available</td>
</tr>
<tr>
<td>D. Schubert et al [14]</td>
<td>2.0 ( \times 10^{19} )</td>
<td>Not available</td>
</tr>
<tr>
<td>V.A Gridchin et al [15]</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td>E. Oermeier et al [16]</td>
<td>1.8 ( \times 10^{19} )</td>
<td>-3.8 ( \times 10^{19} )</td>
</tr>
</tbody>
</table>

Therefore, it is confirmed without inconsistency with published data that the \( \pi \) of the piezoresistor increases with a decrease in the cross section area. On the contrary, \( \pi \) is much smaller than values for conventional piezoresistors. This reason was already mentioned above.

6 CONCLUSIONS

In order to confirm an ability of the poly-Si nano wire piezoresistor as a sensing element of a mechanical sensor, current-voltage (I-V) characteristics and the piezoresistive effect were investigated. The poly-Si nano wire piezoresistor, whose thickness is 32 nm and width is 53 nm, was fabricated by the combination of the electron beam (EB) direct writing and RIE.

A remarkable phenomenon was observed. The longitudinal piezoresistive coefficient \( \pi_l \) of the nano wire piezoresistor increased with a decrease in the cross section area. The maximum value of the longitudinal piezoresistive coefficient \( \pi_l \) of the nano wire piezoresistor is \( 2.2 \times 10^{-5} \) (1/MPa) at \( N = 5 \times 10^{19} \) (cm\(^{-3}\)) and it has enough sensitivity for mechanical sensor application. However, the physical interpretation of this phenomenon still remains.

The piezoresistive effect under various temperature conditions will be investigated as a future work, in order to confirm the extended ability of the poly-Si nano wire piezoresistor as the sensing element of the mechanical sensor.

(Manuscript received June 16, 2000, revised Nov. 22, 2000)

REFERENCES

(2) e.g., Digest of Technical Papers of Transducers'99 (1999).
(16) E.Obermeier and P.Kopystynski, Polysilicon as a material for microsensor application, 30, 149 (1992).
Yasutada Tanimoto (Student-Member)

He received the B.S. degree in 1999 in Mechanical Engineering from Ritsumeikan University, Shiga, Japan. He is currently a master course student of Graduate School of Ritsumeikan University.

Toshiyuki Toriyama (Member)

He received the B.S. degree in 1985, the M.S. degree in 1987, in Mechanical Engineering from Ritsumeikan University, Shiga, Japan, and Ph.D. degree in 1994 from Kyushu University, Fukuoka, Japan. He is now a research fellow in New Energy and Industrial Technology Development Organization (NEDO). His current interests are piezoresistance in advanced semiconductor materials and its application to micro mechanical sensors.

Susumu Sagiyaama (Member)

He received the B.S. degree in Electrical Engineering from Meijo University, Nagoya, in 1970, and the Dr. E. degree from Tokyo Institute of Technology, Japan, in 1994. From 1965 to 1995, he was with Toyota Central Research & Development Laboratories, Inc., where he worked on semiconductor strain gages, silicon pressure sensors, integrated sensors and micromachining. While there, he was a Senior Researcher, Manager of the Silicon Devices Laboratory, and Manager of the Device Development Laboratory. Since 1995 he has been with Ritsumeikan University, Shiga, Japan, where he recently serves as a Professor in the Department of Robotics, Faculty of Science and Engineering. He is Vice Director of Synchrotron Radiation Center and Director of Research Center for Micro System Technology at Ritsumeikan University, Editor-in-Chief of Sensors and Materials. His current interests are microsensors and microactuators and high aspect ratio microstructure technology. He is a member of the IEEE, Japan Society of Applied Physics, the Robotics Society of Japan, the Society of Mechanical Engineers and Japan Institute of Electronics Packaging.