Paper

Characteristics of Polycrystalline Si Nano Wire Piezoresistors

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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 π_l of the nano wire piezoresistor increased with a decrease in the cross section area, while the transverse piezoresistive coefficient π_t was approximately zero and invariant despite variation of the cross section area. The maximum value of the longitudinal piezoresistive coefficient π_l of the nano wire piezoresistor was 22 x 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)-(5). 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 piezoresitor as shown in Fig.1, the piezoresistive effect can be expressed as follows(6):

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \tag{1}$$

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

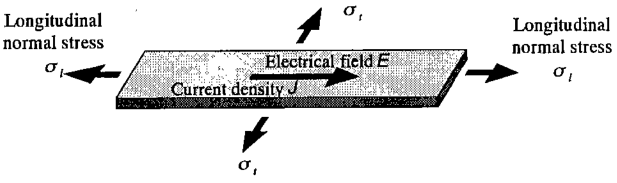


Fig.1 Piezoresistor subjected to biaxial normal stresses.

3 FABRICATION PROCESS OF POLY-Si PIEZORESISTORS

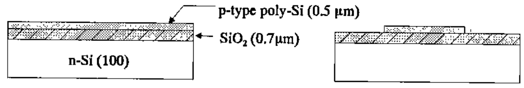
Figure 2 shows the fabrication process of the poly-Si piezoresistors. Nano wire structure of the piezoresistor can be realized by using the EB direct writing and RIE processes.

(a) A SiO_2 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 SiO_2 layer by LPCVD. Impurity concentration *N* of the poly-Si layer was controlled by boron ion implantation. $N = 5 \times 10^{19}$ (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.

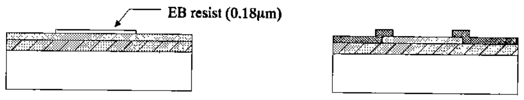
(c) The piezoresistors were fabricated by SF_6 RIE, where EB resist was used as an etching mask.

(d) Electrodes were fabricated by Al vacuum evaporation and photolithography. Finally, sintering was done in dry N_2 at 450℃ for 30 min.



(a) SiO_2 deposition (thermal oxidation) Poly-Si deposition (LPCVD)

(c) Poly-Si piezoresistor formation by RIE



(b) Piezoresistor patterning Formation by EB direct writing

(d) Al electrode formation by wet etching

Fig. 2 Fabrication process of poly-Si piezoresistors.

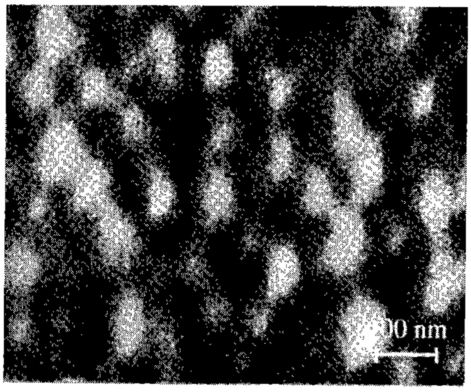


Fig.3 SEM micrograph of grains and grain boundaries

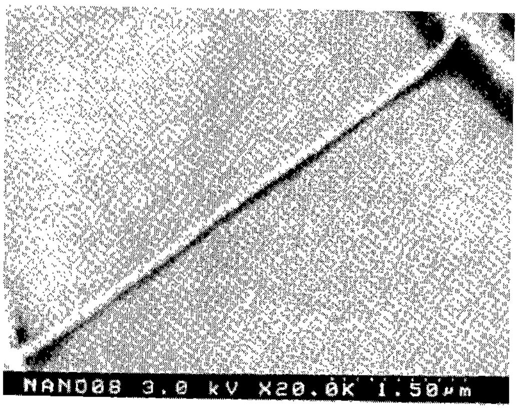


Fig.4 SEM micrograph of the fabricated nano wire piezoresistor (width = 53 nm, thickness = 32 nm).

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 Table1. 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 Ddimension and resistance of the fabricated nano wire piezoresistors.

Specimen No.	Thickness (μm)	Width(μm)			Length (μm)	Cross section ($μm^2$)	Aspect ratio	Resistance(kΩ)	
		top	mean	bottom				calculation	experiment
1	0.547	3.591	3.74	3.88	40	2.04	0.15	1.5	1.6
2	0.547	0.591	0.74	0.88	6	0.40	0.74	1.2	1.7
3	0.196	0	0.16	0.312	6	3.06E-02	1.26	15.2	11.2
4	0.108	0	0.13	0.263	6	1.42E-02	0.82	32.7	40.2
5	0.032	0	0.053	0.105	6	1.68E-03	0.61	277	1457

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:

$$\sigma = E_{poly-Si}\ \varepsilon \qquad (2)$$

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

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

Figure 8 shows the relation between the piezoresistive coefficients π_l and π_t , and the cross section area of the piezoresistors. The longitudinal piezoresistive coefficient π_l of the nano wire piezoresistor increased with a decrease in the cross section area, while the transverse piezoresistive coefficient π_t 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 π_l is resistivity enhancement phenomenon. The five times enhancement of the resistivity from initial value corresponds to approximately 18% increment of π_l for the

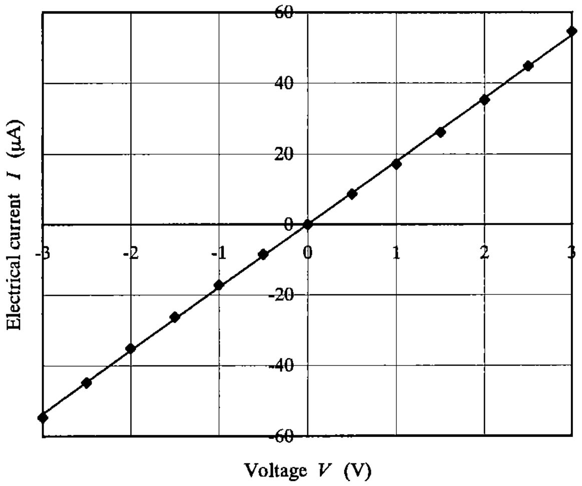


Fig. 5 Current-voltage (I-V) characteristics of the nano wire piezoresistor under room temperature.

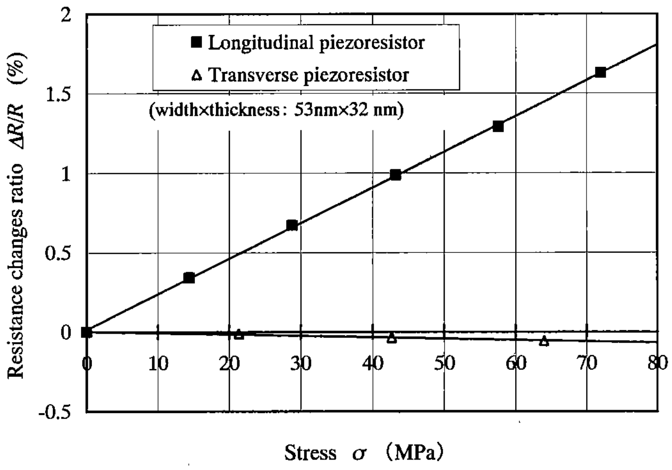


Fig.6 Resistance change in the nano wire piezoresistor due to applied stress under room temperature.

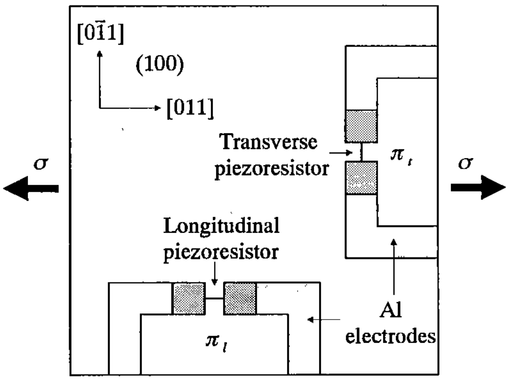


Fig.7 Arrangements of piezoresistors against crystallographic orientations of Si (100) substrate and direction of applied stress.

conventional p-type poly-Si piezoresistors $^{(11)\text{-}(16)}$. As can be seen from Fig.8, the maximum increment of the π_l is approximately 30% with the decrease in the cross section area and higher than this. Therefore, the increment of the π_l 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 = 5x10 ^{19} (cm^{-3}). 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 σ whose direction is perpendicular to the longitudinal direction of the nano wire piezoresistor. A stress gradient in the transverse normal stress σ_t through the thickness is induced into the nano wire piezoresistor. While, σ_t is almost invariant through the width and length. An average of the transverse normal stress σ_t through the transverse cross section area can be estimated by

$$\overline{\sigma_t} = \left(\int \sigma_t \, dA\right) / \left(\int dA\right) \qquad (3)$$

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 σ_t is not efficiently transmitted from the substrate into the nano wire piezoresistor. This is reason why the apparent transverse piezoresistive coefficient π_t was relatively small.

Maximum value of the longitudinal piezoresistive coefficient π_l of the nano wire piezoresistor is 22 x 10^{-5} (1/MPa) at N = 5 x 10 ^{19} (cm^{-3}) and this value has enough sensitivity for mechanical sensor application.

Table 2 shows comparison of the piezoresistive coefficients π_l and π_t of conventional p-type poly-Si piezoresistors with the present poly-Si nano wire piezoresistor. The π_l and π_t of conventional p-type poly-Si piezoresistors are obtained from the gauge factors G by multiplying $E_{poly\text{-}Si}$ =170GPa to G $^{(17)}$. As can be seen from Table 2, the present π_l is lager than values for conventional piezoresistors at N = 5 x 10 ^{19} (cm^{-3}).

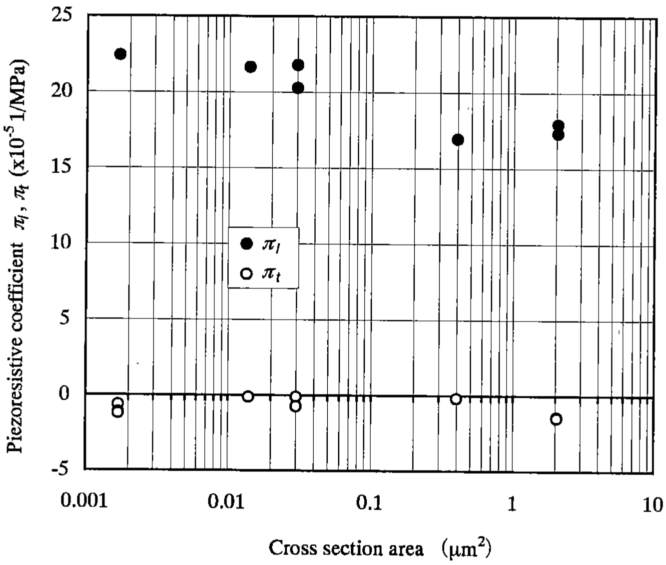


Fig.8 Relation between piezoresistive coefficients π_l and π_t, and cross section area of nano wire piezoresistors.

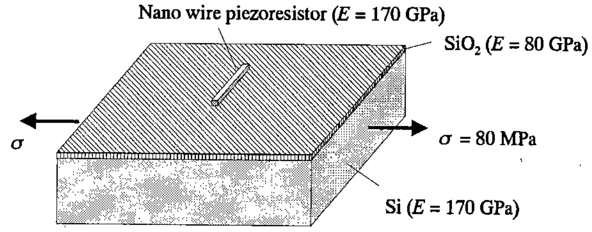


Fig.9 FEM analysis model.

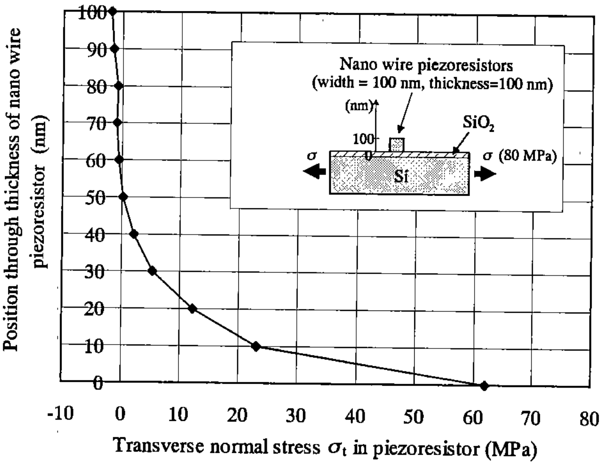


Fig.10 FEM stress analysis for nano wire piezoresistor (width = 100 nm, thickness=100 nm).

Table 2 Comparison of piezoresistive coefficients for conventional *p*-type poly-Si piezoresistors.

		Longitudinal piezoresistive coefficient π_l ($\times$ 10^{-5} MPa^{-1})			Transverse piezoresistive coefficient π_t ($\times$ 10^{-5} MPa^{-1})		
Impurity concentration (cm^{-3})		1×10^{19}	5×10^{19}	1×10^{20}	1×10^{19}	5×10^{19}	1×10^{20}
Authors	Germer and Todt [11]	17.1	13.8	10.9	Not available	Not available	Not available
	P.J.French and Evans [12]	22.5	20.6	18.8	-9.4	-9.8	-8.8
	M. Le Berre et al [13]	20.6	20	18.8	Not available	Not available	Not available
	D.Schubert et al [14]	20.6	16.9	13.1	0	-1.88	-1.88
	V.A Gridchin et al [15]	Not available	Not available	13.3	Not available	Not available	-6.6
	E.Oermeier et al [16]	18.4	16.3	13.1	-3.8	-5	-3.8

Therefore, it is confirmed without inconsistency with published data that the π_l of the piezoresistor increases with a decrease in the cross section area. On the contrary, π_t 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 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 π_l of the nano wire piezoresistor increased with a decrease in the cross section area. The maximum value of the longitudinal piezoresistive coefficient π_l of the nano wire piezoresistor is 22 x 10 $^{-5}$ (1/MPa) at N = 5 x 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.

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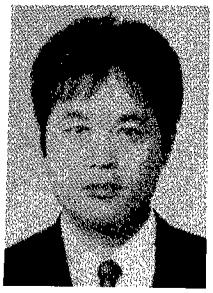

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