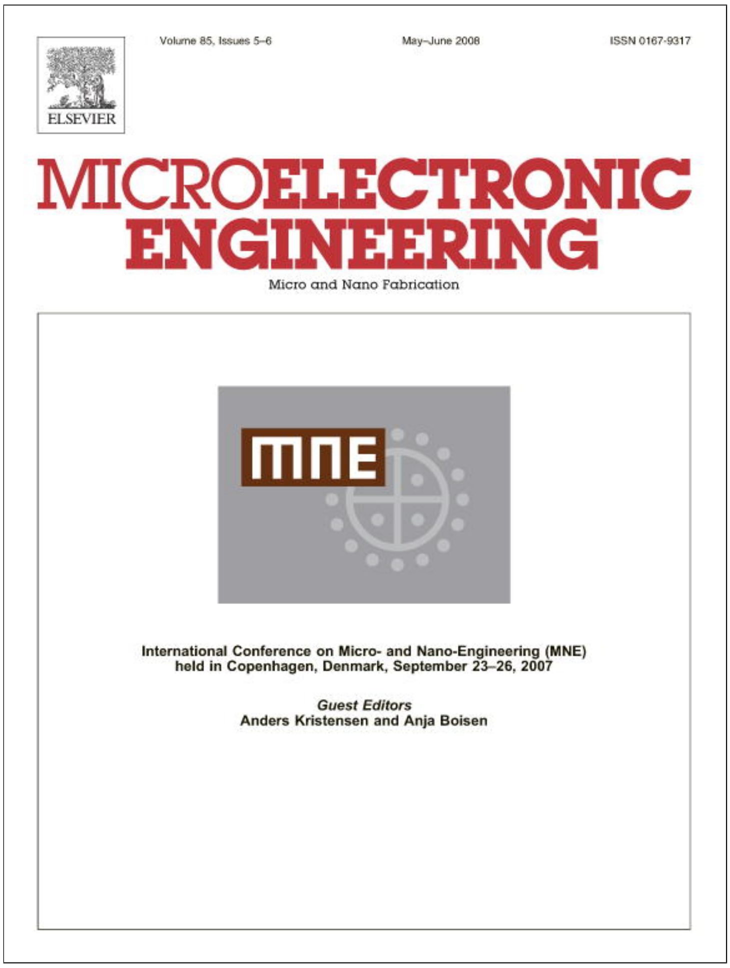
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Measurement of the gauge factor of carbon fiber and its application to sensors

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Abstract

The electrical properties of carbon fiber (CF), an attractive material for strain gauges that can also be applied to resonating sensors, are reported in this paper. The CFs were manufactured from polyactylonitrile (PAN). The fabricated CFs had a 10 μm diameter and a length of several cm. The electrical resistivity of the CFs was found to be about $3 \times 10^{-3}\ \Omega$ cm. The gauge factor of the CF was also observed, and it was found to be about 100–400, depending on the structure of the CF. For the resonating sensor applications of the CF, it was selectively placed in the gaps between the Al electrodes through dielectrophoresis. When the CF was resonated at the 5th resonance mode, a large change of its resistance was observed through an electrical system. The results of the experiment were found to coincide with the calculation results.

Keywords: Carbon fiber; Piezoresistive effect; Electrophoresis; Resonator

1. Introduction

Monocrystalline silicon can be created with the use of a Czochralski crystal puller or by carefully controlling the diffusion process. The name "monocrystalline" implies that the crystal contains no independent grains or grain boundaries. The actual piezoresistive behavior of monocrystalline silicon is highly anisotropic, meaning that its gauge factor is dependent on the orientation of the applied stress as well as on the applied and measured current and voltage, respectively [1,2]. Due to the difficulty of monocrystalline silicon growth on substrates, polycrystalline silicon is also widely applied in sensor and actuator applications [3]. Polycrystalline silicon reaches 60–70% of the piezoresistive sensitivity of monocrystalline silicon and has a much higher sensitivity to strain changes than to metals [4]. The response of polysilicon sensors, however, is highly temperature-dependent [5], which affects their ability to sense true strain parameters. Furthermore, they must be fabricated in a high-temperature environment, which excludes the possibility of integrating them onto polymer MEMS devices (i.e., low-cost microfluidic devices). The first issue can be solved by using a temperature compensation circuit. The second issue, however, cannot be addressed.

On the other hand, CFs were recently shown to exhibit a piezoresistive effect [6]. Based on an order of estimate calculation, the gauge factor of CFs is projected to be about ~400, which is 5–10 times higher than the gauge factor of conventional polysilicon-based strain sensors. Moreover, CFs stand out as a strong candidate for use as a novel sensing material due to their inherent properties, such as their small size (diameter: ~10 μm) and good electrical and mechanical properties. Hence, the aim of this study was to formulate experimental techniques to conclusively test the piezoresistive effects of CFs and to develop fabrication processes for the integration of CFs into micromachined sensors.

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2. Carbon fiber and its gauge factor

Each carbon fiber is a bundle of many thousand carbon filaments. A single CF filament is a thin tube (with a diameter of 10–14 μm) that consists almost exclusively of carbon. The atomic structure of CF is similar to that of graphite, consisting of sheets of carbon atoms arranged in a regular hexagonal pattern. The difference lies in the way these sheets interlock. Graphite is a crystalline material whose sheets are stacked parallel to one another, in regular fashion. The chemical bonds between the sheets are relatively weak, giving graphite its soft and brittle characteristics. CF is an amorphous material: the sheets of carbon atoms are haphazardly folded or crumpled together. This interlocks the sheets, preventing slippage and greatly increasing the strength of the material. The

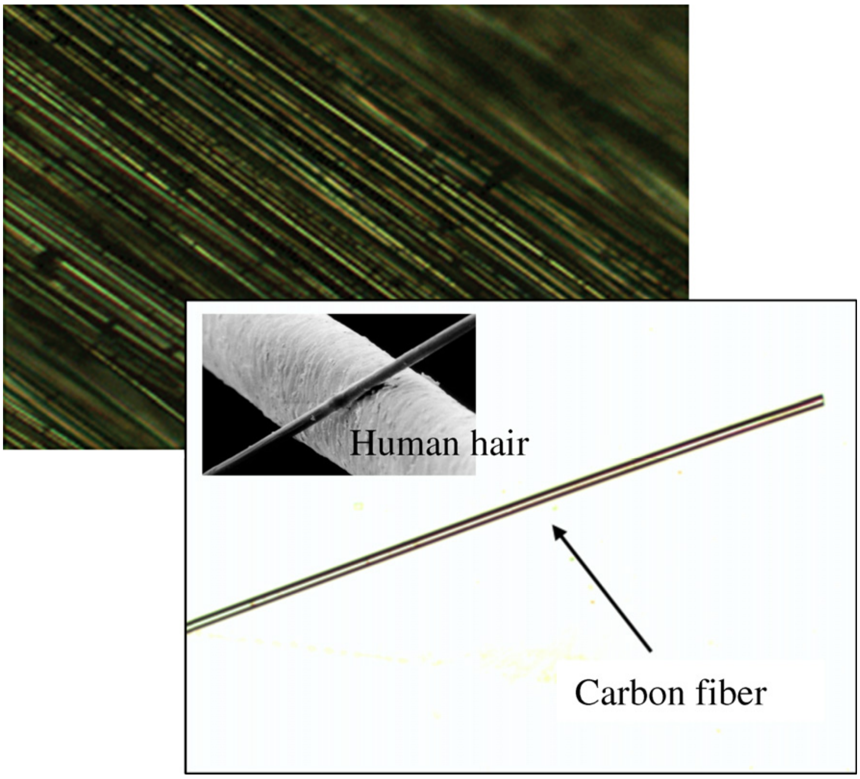

Fig. 1. Optical images of the carbon fibers.

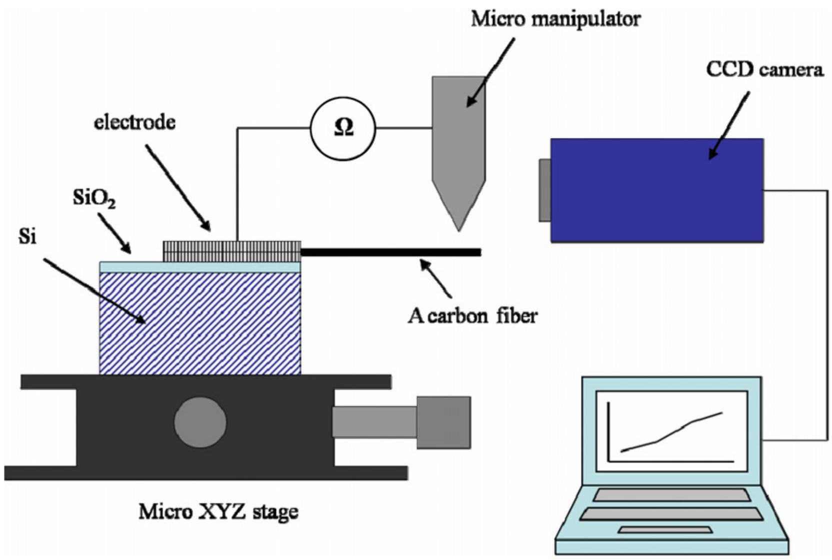

Fig. 2. Experimental setup to measure a gauge factor of the carbon fiber.

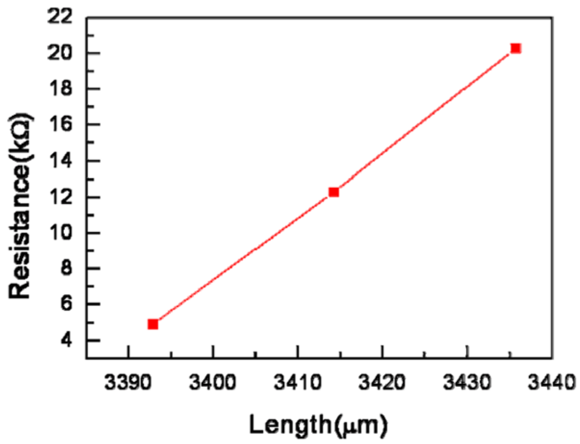

Fig. 3. Resistance change as a function of length change.

density of carbon fiber is about 1750 kg/m^3. It has high electrical and low thermal conductivity. Hence, it can be used as sensors instead of heaters, its current application in the industry.

In this paper, CFs manufactured from polyacrylonitrile (PAN) were used instead of those manufactured from pitch, which were used in the researchers' previous report [6], because the former have better electrical properties and shapes compared to the latter. A common method of making such CFs is through the oxidation and thermal pyrolysis of PAN. In general, it could be created by using a polymer based on acrylonitrile. Like all polymers, polyacrylonitrile molecules are long chains that are aligned in the process of drawing continuous filaments. When it heated in the correct conditions, the non-carbon constituents evapo-

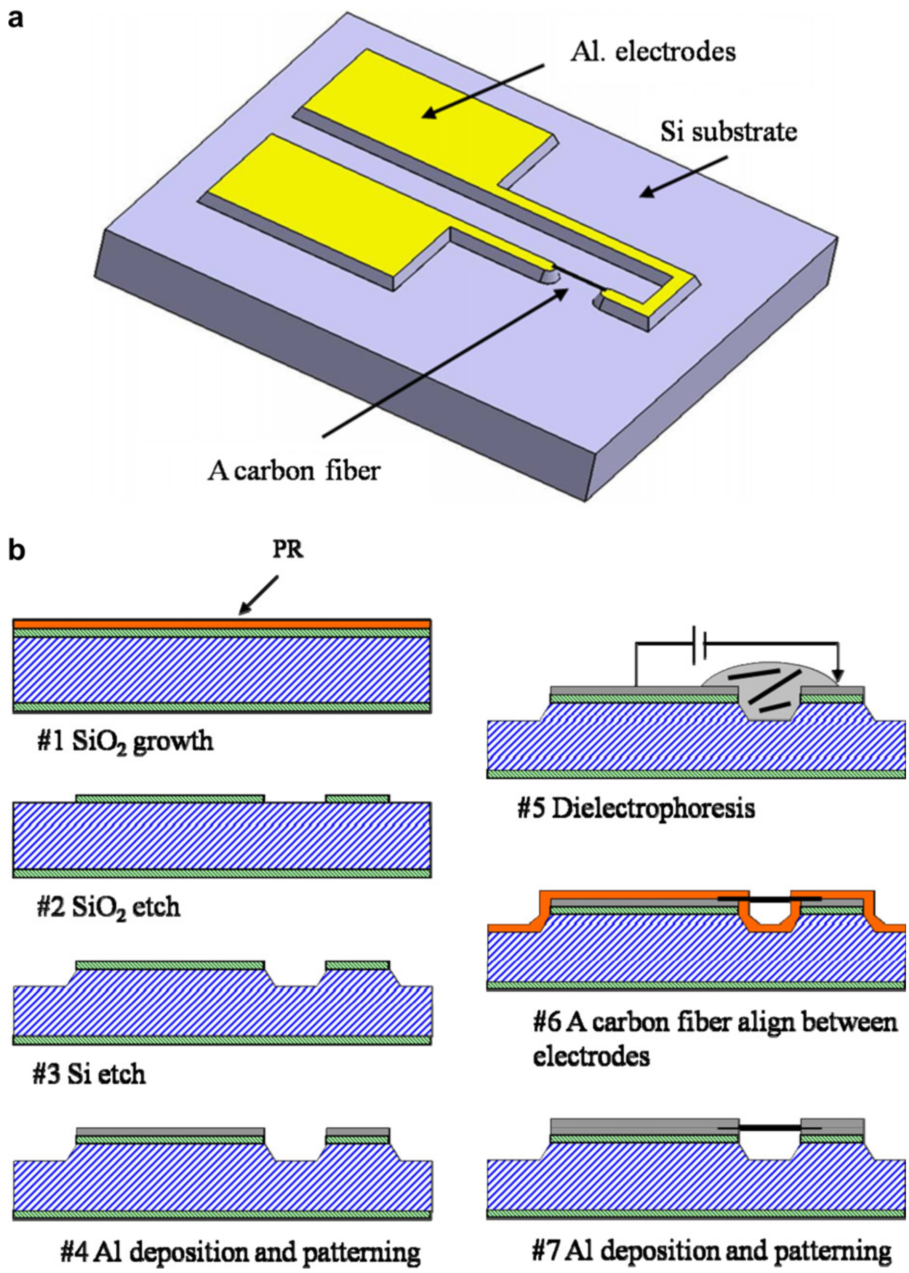

Fig. 4. (a) A schematic diagram of a resonating sensor based on the carbon fiber and (b) process flow for the sensor fabrication.

rate, and the chains bond side-to-side (ladder polymers) and form narrow graphene sheets, which eventually merge to form a single, jelly-roll-shaped or round filament. The result is usually 93–95% carbon. Fig. 1 shows optical microscope images of the CFs that were used in this study.

Fig. 2 shows the experimental setup to measure the gauge factor of the CF. A silicon wafer was thermally oxidized in steam for electrical isolation from the CF. Next, Al electrodes were formed on the silicon dioxide layer using the lift-off process. An ultrasonic cleaner was then used to select a good single CF from the bundle as it is an effective method for this purpose. After the CF bundles were cut using a mechanical method, the CFs were premixed using a standard stirrer and were then homogenized in the ultrasonic flow. Several CFs were obtained by evaporating ethanol, which was used as a solution in place of DI water. Due to the chemical nature of carbon, it was difficult for CF to disperse in water. One of the ends of a selected single CF was exactly placed on an Al electrode using a microtweezer. Al was then re-evaporated and patterned to decrease the contact resistance between the CF and the electrode. As shown in Fig. 2, a certain force was applied to the free end of the CF using a conductive tip manipulated by a micromanipulator. The bending characteristics as a function of the applied force were then observed through a CCD camera. The electrical properties, shown in Fig. 3, were measured using a source meter under various applied forces. Linear increase of resistance as a function of length was observed. The results of the experiment were then compared to those of the simulation so that the force strength applied to the CF and the maximum strain induced on the CF could be determined. By comparing such results, the gauge factor (K) of CF could be estimated. The conventional equation given by $K = \Delta R/R \times e$ (where, ΔR and e denote the relative increase of length of the resistance and the element, respectively. R is the stress free resistance) was used to find the gauge factor. The calculated K of the used CF was about 100–400, depending on the CF. It is 5–10 times higher than that of the conventional polysilicon-based strain sensor. Resistivity within the range of room temperature was also observed, and it was found to be about $1.5–3.0 \times 10^{-3}\ \Omega$ cm.

3. Carbon-fiber-based resonating sensor

Since nanotubes have an extremely small cross-section, it is difficult to realize a nanotube-based resonator with conventional actuation and detection methods. Hence, a new resonator is proposed in this paper based on the carbon material. Fig. 4a shows a schematic cross-sectional view of the doubly clamped CF that was used in this paper. The CF was made to contact with two metal electrodes (Al), and the silicon substrate separated from the CF by an oxide layer was used. The CF is either partially or fully suspended across a trench in silicon dioxide. The suspended CF devices were fabricated according to a process shown in Fig. 4b. There are three major parts in fabrication, namely: (1) making CFs; (2) making electrical contacts; and (3) suspending the CFs with the use of the Al electrodes. After making a CF, the silicon wafer is thermally oxidized in steam and is then patterned to make grooves into the silicon. Next, Al electrodes are defined on top of the oxide layer using a lift-off process, and the CFs are selectively placed between the Al electrodes through dielectrophoresis (DEP), which is described in Ref. [6]. To validate the consistency of the batch assembly of the CF-based devices, repeated experiments on the DEP manipulation of the CFs between the arrays of Al electrodes were performed, and plots of statistical data for the different experiments were generated. Finally, a second metal layer was evaporated, typically 100 nm of Al, and was patterned to contact the CFs. Fig. 5 shows a scanning electron microscope image of a suspended CF crossing a trench formed through wet-etch. In the experiment, a CF with a length of 858 μm and a diameter of 14 μm was used. A simulation method was employed to determine the resonance characteristics of the suspended CFs, which had several vibration modes according to their resonance characteristics. Fig. 6 shows the results of the simulation of the CF resonator that oscillates at the 5th resonance mode. The 5th resonance frequency that was obtained through calculation was about 1.5 MHz. This result allows to us to imagine not only the resonance frequency of the used CF but also its mode. The device was placed on a piezoelectric actuator (PA), and the clamped CF resonator is driven by means of the PA vibrated with AC voltage. The resonance characteristics of each vibration mode were detected through an electrical system and an optical system with a high resolution. The 5th resonance mode of the CF was clearly observed at 1.4 MHz, and the result was very close to that of the simulation (1.5 MHz). The total change in resistance at the maximum deflection of the 5th resonance mode was 18.7 Ω, which was determined with the use of a function generator and an oscilloscope, as shown in Fig. 7. These

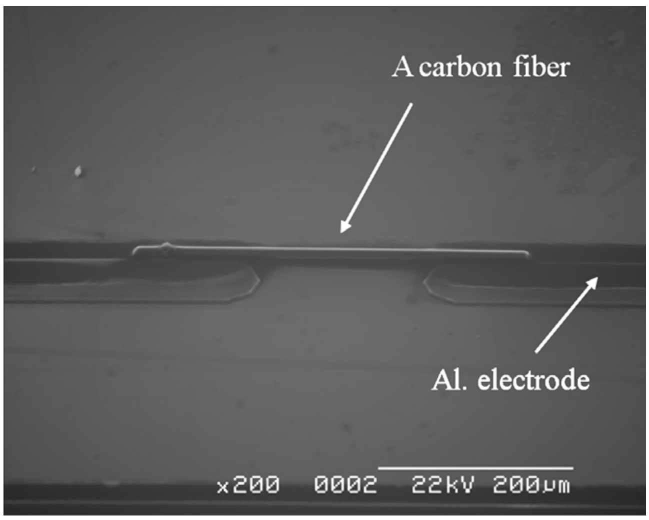

Fig. 5. A scanning electron microscope image of the fabricated resonating sensor.

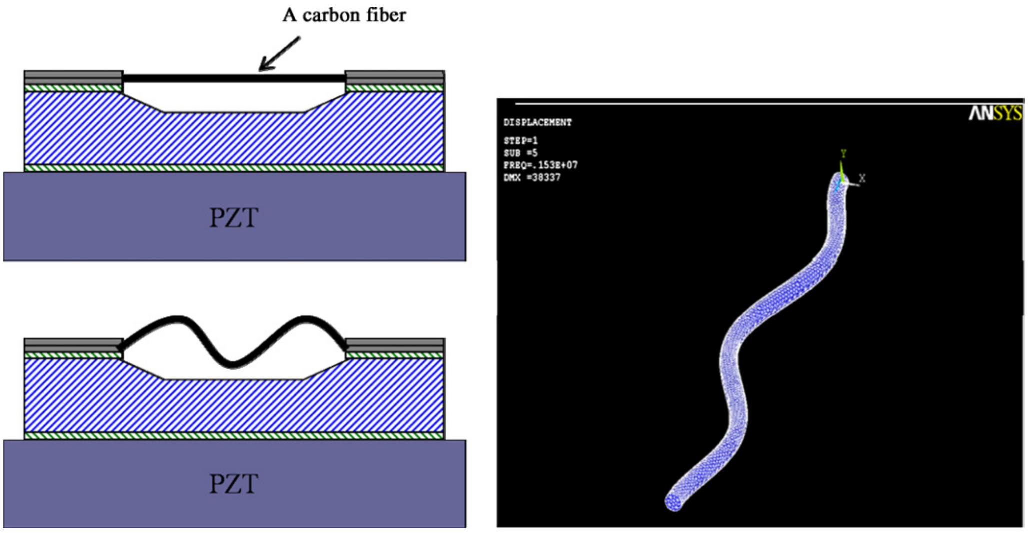

Fig. 6. A simulation result of the vibrating carbon fiber at 5th resonance mode (1.4 MHz).

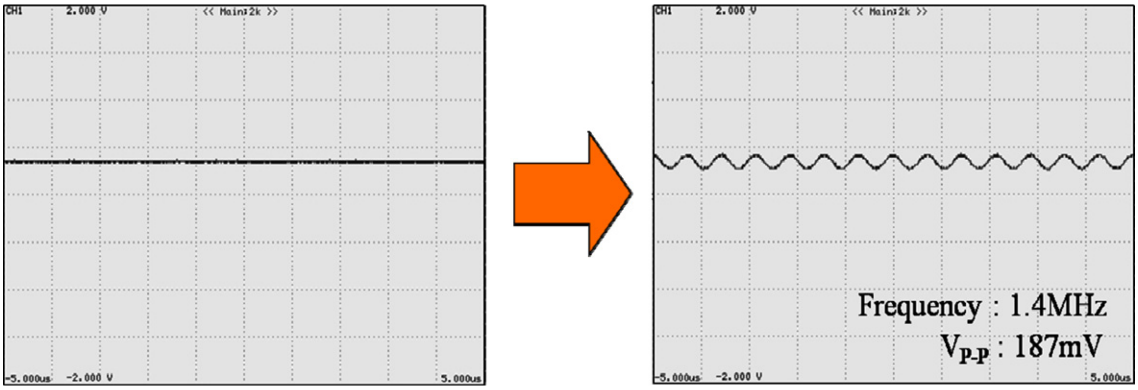

Fig. 7. Electrical output when the CF is vibrated at 1.4 MHz by a piezoactuator.

results indicate that the CF-based resonators can be applied to micromachined sensors.

4. Conclusions

A new piezoresistive sensing element, carbon fiber (CF), is proposed in this paper for MEMS applications. The use of CF as a piezoresistor has some advantages over the use of the conventional piezoresistor made with doped silicon. In sensor applications, CF showed a much higher sensitivity compared to the polysilocon-based piezoresistor due to the high gauge factor. The CF does not require high-temperature processes during sensor fabrication. Furthermore, the optimized dielectrophoretic (DEP) process based on CF provides a fast and efficient method of sensor fabrication. It was also proven that the success rate of the batch assembly of the CF-based sensors is higher than 80%, which shows that the DEP manipulation of CF is a feasible technology for the manufacture of batch-assembled CF sensors. A feasibility test of the resonating CF sensor was performed using a simple experimental setup, and the result of the test show that CF can be used as a new sensor material.

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References

[1] J.W. Dally, W.F. Riley, Handbook of Experimental Mechanics. Chapter 2. Strain Gauge, Prentice-Hall Englewood Cliffs, 1987, pp. 41–78.
[2] S. Keil, Report Appl. Measurem. 4 (1) (1988) 15–17.
[3] V.V. Grishenko, V.M. Lubimsky, A.A. Kharkov, Electron Devices and Materials (EDM) 2000, Siberian Russian Student Workshops on, 2000, pp. 141–148.
[4] W.K. Schomburg, J. Micromech. Microeng. 14 (2004) 1101–1108.
[5] Örjan Vallin, J. Micromech. Microeng. 10 (2000) 196–199.
[6] C.S. Park, B.S. Kang, D.W. Lee, Microelectron. Eng. 84 (2007) 1316–1319.