A novel method using SiNW to measure stress in cantilevers*

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Abstract: A silicon (SiNW) nanowire device, made by the bottom-up method, has been assembled in a MEMS device for measuring stress in cantilevers. The process for assembling a SiNW on a cantilever has been introduced. The current as a function of the voltage applied to a SiNW have been measured, and the different resistances before and after cantilever releasing have been observed. A parameter, η, has been derived based on the resistances. For a fixed sample, a linear relationship between η and the stress in the cantilever has been observed; and, so, it has been demonstrated that the resistance of SiNW can reflect the variation of the cantilever stress.

Key words: SiNW; stress; cantilever; MEMS

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1. Introduction

Silicon nanowires (SiNWs) are a unique form of nanosilicon, which are grown by direct synthesis (bottom-up) rather than by the conventional lithography patterning (top-down) approach. So, a SiNW is considered as an interesting alternative architecture to the conventional planar technology for devices at the end of the ITRS roadmap[1, 2].

Until now, in research all over the world, breakthroughs on the SiNW have been made on all aspects, such as the device preparation, the analysis of the device properties, and the methods of assembling into a wide range of nanoscale electronic devices and circuits. The great opportunities for SiNWs should range from high-density, scalable, and integrated nanoelectronics to ultra-sensitive nanoscale sensors for chemical and biological detectors[1–5].

For MEMS devices, especially for those working in mechanical field, the measurement of the residual stress is important in predicting service life, analyzing distortion, and for determining the reason for failure[6]. Stampfer *et al.*[7] have proposed that single-walled carbon nanotube (SWCN) can act as a pressure sensor. An electromechanical sensor device consists of an individual electrically connected single-walled nanotub (SWNT) adsorbed on top of a layer.

We use a SiNW as the sensor to measure stress in a cantilever. As an individual device, it can be prepared and integrated into the cantilever by the bottom-up approach, without influencing the properties and technological process of MEMS. The preparation method and assembly will be introduced later. The measurement result and the relationship of the current of the SiNW and the stress also will be introduced.

2. Sample preparation and measurement

The MEMS cantilever was made by a conventional process that is compatible with the CMOS process. Here, a polysilicon cantilever sample is used to demonstrate the proposal that its stress could be measured by using a SiNW. The process is illustrated in Fig. 1. First, the substrate was prepared, being ⟨110⟩ silicon, which was P-type doped at 10^{14} cm^{-3} (Fig. 1(a)). Consequently, as shown in Fig. 1(b), a sacrificial oxide layer was grown on the surface and the anchor part has been patterned. Then, the polysilicon layer, which acts as the cantilever part in the finished device, was deposited on top of the surface (Fig. 1(c)). To guarantee the electric isolation of the cantilever from the SiNW, a patterned thin Si_3N_4 layer with a thickness of about 10 nm has been deposited on the surface. To decrease its influence on the residual stress, only those parts of Si_3N_4 corresponding to the positions of SiNW terminals will be maintained, as shown in Fig. 1(d). Then, a SiNW was assembled onto the surface of the cantilever to act as the measuring cell (Fig. 1(e)). After that, two polysilicon pads were used to fix the SiNW terminals. Finally, the cantilever was released by removing the pre-deposited sacrificial layer, as shown in Fig. 1(f).

The SiNW in this paper has been synthesized by the vapor-liquid-solid method, in which Au clusters were used as a solvent at high temperatures. The Si and Au formed a liquid alloy. When this alloy became supersaturated with Si, the SiNW grew by precipitating at the liquid-solid interface. A SiNW was grown from 20-nm-Au nanoclusters, and the average nanowire diameters were 20 ± 2 nm. The length of the well-defined nanowires can be controlled by adjusting the growth time during the synthesis process. Based on the Si–Au phase diagram, the growth temperature is 435 °C. The pressure of the CVD reactor was evacuated to less than 100 mTorr. The SiH_4 flow was 50 sccm. The electronic properties of SiNWs can be precisely controlled by introducing dopant reactants during growth. The ratio of silane to diborane reactants during the growth is $SiH_4 : B_2H_6 = 4000 : 1$[8]. Four-point resistance measurements were carried out on the doped SiNW. Based on the SIMS data, the nanowires should be doped with a high

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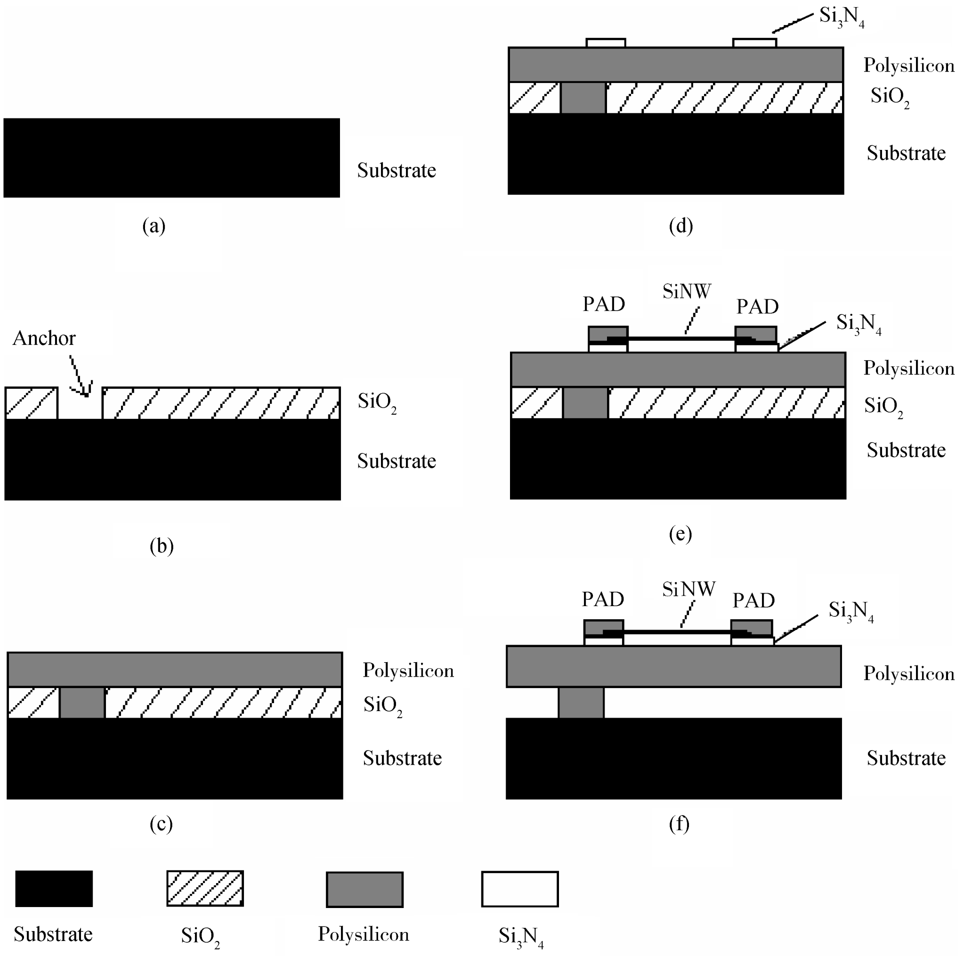

Fig. 1. Schematic of the process: (a) Preparation of the substrate; (b) Deposition of a sacrificial layer and patterning on the anchor position; (c) Deposition of a polysilicon layer using LPCVD; (d) Deposition of a Si_3N_4 layer acting as an isolation layer; (e) Assembling a SiNW and bonding on top of the isolation layer; (f) Releasing the cantilever by moving the pre-deposited sacrificial layer.

boron concentration in the range between 4×10^{18} and 1×10^{19} cm^{-3}.

The profile structure of the terminal of the grown SiNW is shown in Fig. 2. The scale bar in the image is 10 nm. It can be observed that the grown structure is similar to the shell-core ones.

After being synthesized, the nanowires were first dispersed into isopropanol by sonication, and then drop-cased onto the MEMS devices. After drying the solvent, there are always some nanowires on the patterned cantilevers. However, their orientations varied without any direction. Here, the method to organize the nanowire on the cantilever is by using STM tips. STM represents an ideal tool for obtaining this critical information. STM has also been shown to be a powerful tool for determining the structure and electronic properties of 1D nanostructures. Since here only one SiNW needs to be assembled, this was easily done with the STM tip[9].

After a SiNW was assembled on the surface along the long axis of the cantilever, two other assistant steps should be followed. These are fastening and fixing of the SiNW. First, the SiNW string should be fastened along the cantilever. Otherwise, if the string is not in the fastened state, the bending of the cantilever will not influence the SiNW. Only a SiNW in a fastened state can sense the cantilever bending. The string fastening process has been done by using STM tips. Moreover, the string should be fixed firmly at the terminals. In order to fix the terminal and to lead out the terminal pads, polysilicon films were locally deposited by the focused ion beam (FIB) technology at the nanowire terminals acting as the electrode, which is n type with a doping level of 10^{18} cm^{-3}. The SEM graphic for the SiNW assembled on the cantilever is shown in Fig. 3. In Fig. 3, the length of the cantilever is 200 μm and the width is 50 μm. For the SiNW on the surface, its length is 135 μm.

The electrical characteristics of the SiNW are different before and after the cantilever is released. Before the cantilever release, as shown in Fig. 1(e), the SiNW's I–V characteristic has been measured. After releasing, as shown in Fig. 1(f), the same measurement has been repeated. Under the influence of the cantilever's residual stress, a bending or curving of the cantilever will occur, changing the characteristics of the SiNW. Utilizing the sensitivity of a SiNW, which is fixed on the cantilever, as a sensor, a change in its electrical characteristics should be observable. So, this is the main principle used here: to use a SiNW to detect the cantilever stress. To satisfy the measurement demand, an electron beam probe has been used here instead of wire bonding. If wire bonding is used here, the weight of it will push the lever down and influence the accuracy of the measured stress.

According to the authors' experimental results, after a

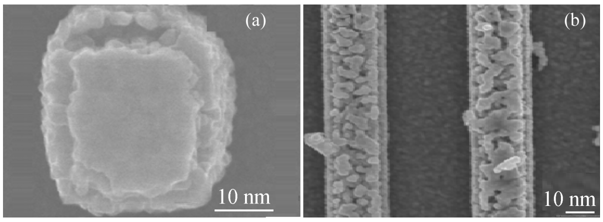

Fig. 2. TEM images of the grown SiNW, where the scale bar is 10 nm: (a) The terminal section profile; (b) The SiNW profile.

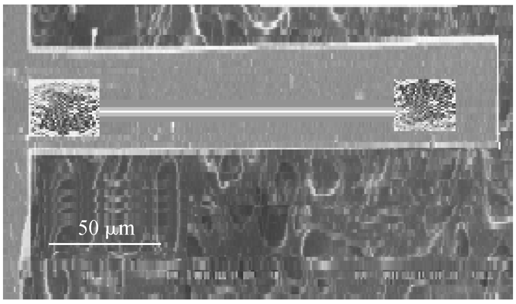

Fig. 3. SEM graph for the SiNW assembled on the cantilever.

SiNW has been assembled on the surface, it is necessary to bake it under a hydrogen atmosphere for at least 2 min in a temperature range from 65 to 80 °C. During this process, hydrogen is mixed with nitrogen and the volume ratio of hydrogen to nitrogen is 3 : 97. The hydrogen atmosphere is helpful to eliminate the dangling bonds on the surface of a SiNW because hydrogen atoms can saturate the dangling bonds. After the process and a release of the cantilever, an obvious difference of the *I*–*V* curve can be observed, as shown in Fig. 4, in which rectangle dots indicate the results before and round dots the results after the cantilever release.

From Fig. 4, an observable difference of current appears after the baking process in the hydrogen atmosphere. For example, the difference of the current is 0.05 μA when the applied voltage is 8 V. The measurement was carried out with a Keithley 4200.

By adjusting the parameters of the baking process, the difference could not be changed any more, even at a prolonged baking time. That means, the effect of the baking process on the surface of the SiNW and the connection between a SiNW and a cantilever can be saturated within the initial several minutes.

3. Experimental result and discussion

Almost all results have shown that the observed current (*I*) versus voltage (*V*) behavior is linear, which means that the terminal contacts are ohmic. Moreover, the conductance ($\mathrm{d}I/\mathrm{d}V$) measured in air at $V = 0$ as a function of time has been stable.

Besides the results in Fig. 4, other measurements have been repeated at different stresses. As shown in Fig. 5, a point stress is applied on the free terminal of the cantilever.

When external force has been applied, the stress on the cantilever will be the a combination of the residual stress and the applied stress. The measurements of the SiNW resistance have been carried out repeatedly using different forces.

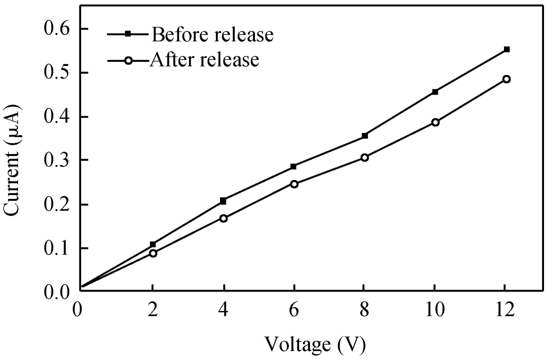

Fig. 4. *V*–*I* curve of SiNW with a baking process in a hydrogen atmosphere.

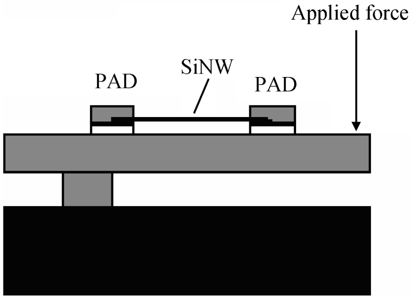

Fig. 5. Schematic for applying a force on the terminal of the cantilever.

A parameter named η is defined based on the measured resistances as:

$$\eta = |R_\mathrm{a} - R_\mathrm{b}| \times \frac{R_\mathrm{a}}{R_\mathrm{b}}, \tag{1}$$

where R_a stands for the SiNW resistance after the cantilever is released, and R_b denotes the resistance before the release.

For a specific sample, the stress is proportional to η, as shown in Fig. 6. This relationship between stress and η has not been clear until now. But this linear dependency can be used to determine the stress in case that the SiNW resistances before and after cantilever release are measured.

For example, if the force applied on the cantilever is unknown, after the resistances have been measured, Equation (1) will be used to calculate the η parameter. Then, according to the curve in Fig. 6, the stress can be calculated.

To verify the linear relationship between the stress and the η parameter, further investigations have been done.

Three cantilevers with different thicknesses of the polysilicon layer have been prepared, which correspond to different residual stresses. After actual measurements with different applied forces, the η parameters for different samples and conditions can be calculated. The curves in Fig. 7 show the relationship between the stress and the η parameter. They all show a linear dependency.

So, based on the above analysis, there indeed exists a linear relationship between the cantilever stress and the η parameter for a cantilever. This relationship is helpful for two reasons. First, it can be used to calculate the value of the stress. For a fixed lever, after its curve as that shown in Figs. 6 and 7 has been determined, any stress can be predicted from a measurement fo η. Second, maybe the linear curve can be used to

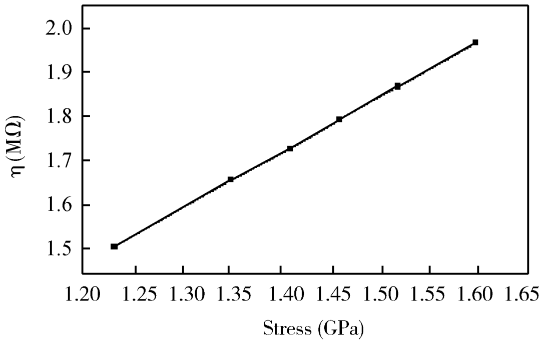

Fig. 6. Relationship between the stress and the defined η.

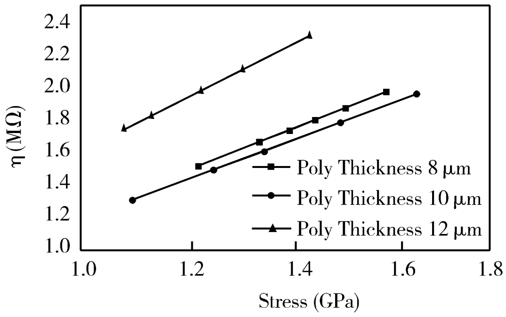

Fig. 7. Three curves showing the relationship of the stress and the defined η, corresponding to three cantilevers with different thicknesses.

investigate the properties of a SiNW by a new method.

4. Conclusion

In this paper, a SiNW has been used to measure the stress of a cantilever in MEMS. The process of a bottom-up method, combined with traditional top-down ones, is used here to demonstrate its feasibility. The concrete method of how to assemble a SiNW on a cantilever has been introduced. A measurement on a SiNW has been carried out to investigate its relation with the cantilever stress. A linear dependency has been found between the derived parameter η and the stress of the cantilever. Other different samples have been used in this investigation to demonstrate the linear relationship.

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