Sensitivity enhancement in SiGe-on-insulator nanowire biosensor fabricated by top surface passivation

Chiung-Hui Lai[1], *Kow-Ming Chang*[2,3], *Chu-Feng Chen*[2], *Cheng-Ting Hsieh*[2], *Chin-Ning Wu*[2], *Yu-Bin Wang*[2], *Chung-Hsien Liu*[2], *Kuo-Chin Chang*[4]

[1]*Department of Electronics Engineering, Chung Hua University, No. 707, Section 2, WuFu Road, Hsinchu 300, Taiwan*
[2]*Department of Electronics Engineering and Institute of Electronics, National Chiao-Tung University, No. 1001, University Road, Hsinchu 300, Taiwan*
[3]*Department of Electronic Engineering, I-Shou University, No.1, Section 1, Syuecheng Road, Kaohsiung 840, Taiwan*
[4]*Tse-An Clinic, Chung Cheng Road, Tse Kuan District, Kaohsiung 319, Taiwan*
E-mail: grapechen@gmail.com

Published in Micro & Nano Letters; Received on 30th March 2012; Revised on 30th May 2012

The oxidation caused by Ge condensation increases the Ge fraction in a SiGe-on-insulator (SGOI) and significantly increases the hole mobility. This effect can be exploited to improve the sensitivity of SGOI nanowires. However, previous studies have found that the sensitivity of SGOI nanowires degrades when the Ge fraction exceeds 20%, because a high Ge fraction destabilises the surface state of SiGe. In this work, a top surface passivation plasma-enhanced chemical vapour deposition SiO_2 layer deposited on a $Si_{0.8}Ge_{0.2}$ nanowire improved its sensitivity by $\sim$1.3 times that of the nanowire sample without a top passivation layer.

1. Introduction: The biological, chemical and optical applications of nanowires are now an important research topic [1, 2]. Nanowires have attracted interest in terms of their use as essential building blocks for functional electronics devices, especially in nanoelectronic devices [3–5] and high-sensitivity biosensors [6, 7]. A major concept of planar semiconductor processes used in biological sensors is surface potential modification. An important feature of a nanowire is their large surface-to-volume ratio, which is crucial for ultrasensitive detection of chemical or biomolecular species. As the conduction depends on the surface charges surrounding the nanowires surface [1], the sensitivity of the nanowire sensor can be enhanced by specialised biomolecular coatings, for example coatings specifically designed to detect viruses, protein, ions or DNA [8–10].

The strategies typically used to fabricate nanowires can be classified as (a) bottom-up approaches; for example thermal evaporation [11], laser ablation and vapour–liquid–solid [12] and (b) top-down approaches; for example advanced photo-emission approaches, such as extreme ultraviolet to X-ray [13], atomic force microscopy [14], nanoimprinting [15] and the use of side-wall spacers [16]. The side-wall spacer technique is the cheapest and the easiest way to fabricate a nanowire sensor.

Strained silicon MOSFETs enhance the electron and hole mobility. For maximum hole mobility, the fraction x of $Si_{1-x}Ge_x$ should be $\sim$0.3 [17]. Thus, the SiGe-on-insulator (SGOI) process [18] has potential applications for fabricating high-sensitivity nanowire sensors. The formation of SGOI nanowires by a Ge-condensation process can enhance the nanowire conductance by increasing the mobility of hole carriers. The sensitivity of the SGOI nanowire can also be enhanced by increasing its surface-to-volume ratio, which then increases condensation of carriers in the conductivity layer, which is extremely thin. In previous studies, the authors increased the surface-to-volume ratio of SGOI nanowires by using a SiGe/α-Si stacking structure [19]. Increasing the Ge fraction in an $Si_{1-x}Ge_x$ nanowire also improves the sensitivity of a nanowire biosensor by increasing the mobility [20, 21]. During the Ge condensation process used to fabricate an ultrathin SGOI with a high Ge fraction, Ge pile-up was observed at the SiO_2/SiGe interface. However, oxidation increased the trap density at the SiO_2/SiGe interfaces by $\sim 10^{12}$ cm^{-2} [22]. The many dangling bonds at the free surface destabilised the surface state of the semiconductor. A high Ge fraction in $Si_{1-x}Ge_x$ was also found to be associated with a high surface state, which accelerated oxidation. A high oxidation rate can further destabilise the process [23]. To increase the stability of the surface state, a thermal SiO_2 passivation layer can be used to reduce the interface state of the SGOI nanowire surface to less than 10^{11} cm^{-2} eV^{-1} [24]. The interface state of the free surface is $\sim 10^{15}$ cm^{-2} eV^{-1}. However, thermal oxide has a high resistance to O atom diffusion because of its high quality and stability. The oxidation rate was degraded by the diffusion of O atoms through the thermal SiO_2 layer. Hence, to effect more Ge rejection from SiO_2 and pile-up at the SiO_2/SiGe interface, increasing the oxidation temperature or oxidation duration for O atom diffusion through the SiO_2 layer was necessary. Increasing the oxidation temperature and duration causes Ge to diffuse away from the surface of SiO_2/SiGe to the bulk of SiGe. The carrier mobility was reduced, caused by the lower Ge fraction at the surface of the SiGe nanowire. In the SiGe nanowire sensors in this work, a plasma-enhanced chemical vapour deposition (PECVD) SiO_2 layer is used as a passivation layer to improve the interface state of the SiGe nanowire. Compared with thermal oxide, PECVD oxide is of a lower quality and density and O atoms can diffuse through in a shorter oxidation duration at a lower temperature. Moreover, the thickness of the thermal oxide layer grown from the SiGe layer is difficult to control than a layer fabricated by PECVD owing to the abnormal oxidation characteristics and enhanced oxidation of the SiGe layer.

2. Experimental procedure: The nanowire samples in this study were fabricated using a side-wall spacer process. The oxide of 300 nm in height was deposited and was patterned as the bottom layer for α-Si/ $Si_{1-x}Ge_x$ deposition. The α-Si was deposited at a thickness of 200 Å by low power chemical vapour deposition (LPCVD) at 650°C and the Ge fractions (7, 14 and 20%) of the $Si_{1-x}Ge_x$ splits were deposited by ultra-high vacuum chemical vapour deposition at 655°C after RCA cleaning of the wafer. To clarify how the passivation layer affects the nanowire sensitivity, two nanowire sensors were fabricated with and without a SiO_2 passivation layer. The SiO_2 layer, which was split into thickness of 100 and 200 Å, was fabricated by PECVD. A poly-Si nanowire was also fabricated for use as a control group to verify the oxidation rate. After the formation of the α-Si/SiGe layer, the samples were treated in the ambient environment (pure N_2, pure O_2 and diluted O_2 gas) for varying durations (3, 5, 7 and 10 min) were varied.

The nanowires were then annealed at 950°C for 180 s in N_2 gas. After annealing, the Al-500 nm films were treated by thermal evaporation followed by Al sintering at 400°C. Finally, the electrodes were defined by the mask process. The poly-Si and SiGe nanowires were implanted in the p-type nanowire. The α-Si/$Si_{1-x}Ge_x$ nanowires were functionalised by using 3-aminopropyltri-ethoxysilance (APTMS) to modify the silicon oxide surfaces surrounding the nanowires. A hydroxyl functional group on the oxide surface was replaced by methoxy groups of APTMS modules, whereas the nanowire surfaces were simultaneously terminated by amine groups. Earlier, the authors reported that the amine groups tend to deplete positive carriers, which reduces the conductivity of the p-type nanowire. Next, bis(3-sulpho-*N*-hydroxysuccinimide ester) sodium salt (BS3) was used as a linker between the APTMS and IgG antibody. The BS3 was prone to becoming negatively charged, which increased the conductivity of the p-type nanowire because of accumulation of holes by BS3 on the nanowire surface. The objective of this study was to compare the variations in conductance (G) and sensitivity (S) of the samples after APTMS surface modification. A Hewlett Packard HP 4156A instrument was used to measure the electrical characteristics of the nanowire sensor. The drain voltage (VD) was varied from −10 to 10 V in steps of 500 mV, and the back gate voltage was 0 V. The electrical characteristics were measured at each stage of the surface modification, and the average conductance was then extracted from the ID–VD characteristics with VD = 3–6 V. The sensitivity (S) of a nanowire-based sensor is defined as the ratio of the magnitude of the change in conductance to baseline conductance

$$S = \frac{|G - G_0|}{G_0} = \frac{\Delta G}{G_0} \quad (1)$$

where G_0 denotes the conductance before capture of a molecule, G is the conductance after molecule capture and ΔG is the difference between G and G_0.

3. Results and discussion: Fig. 1 presents characterisation of the I–V curve for α-Si = 200 Å/$Si_{0.86}Ge_{0.14}$ nanowires with and without a passivation SiO_2 layers. In the work of Hanrath *et al.* [25], Ge nanowire exhibited p-type behaviour, where Ge tends to accumulate holes at the surface as a result of a trapped negative surface charge. Hence, the bare SiGe nanowire sample without a passivation SiO_2 layer should have a higher conductance than the passivated SiGe nanowire sample. Fig. 1 shows that the conductance of a nanowire with a 200 Å thick SiO_2 passivation layer was higher than that of a nanowire with a 100 Å thick passivation layer and higher than that of one without a passivation layer. This conflict was caused by enhanced surface doping; hence, ionised impurity carrier scattering and/or surface scattering is of major concern regarding conductance variation [24, 26]. The nanowire sensitivity can be improved by increasing the conductance, which increases the mobile carriers near the nanowire surface. Sensitised carriers can then increase without being trapped by the interface state. Fig. 2 shows the sensitivity of the nanowire sample was shown in Fig. 1 after APTMS modification. The progressive increase in sensitivity observed in Fig. 2 correlated with the progressive increase in conductivity in Fig. 1. Fig. 3 plots the sensitivity of the SiGe nanowires structure for different fractions of Ge condition. Increased sensitivity was observed in nanowires capped with a passivation layer. The sensitivity increase observed in the $Si_{0.8}Ge_{0.2}$ nanowire exceeded that in other SiGe nanowire samples. However, the sensitivity of the $Si_{0.8}Ge_{0.2}$ nanowire sample was poorer than that of the other nanowire samples with a lower Ge fraction when no passivation layer was used to cap the SiGe nanowire. This finding is consistent with our previous work [20], which showed that the sensitivity of a SiGe nanowire was degraded when the fraction of Ge exceeded 14%. Therefore the sensitivity of the SiGe nanowire increased with the fraction of Ge when a suitable capping layer was used. Fig. 4 compares the sensitivities of samples of a 20% Ge nanowire following after treatment under various ambient conditions. Treatment in pure ambient N_2 did not increase the sensitivity because Ge condensation did not occur without O_2 gas. The sensitivity of the pure O_2-treated nanowire sample was lower than that of the sample that treated with a mixture of O_2 and N_2. Treatment with pure O_2 gas, however, produced an increased Ge pileup at the nanowire surface during the Ge condensation process and a corresponding increase in the

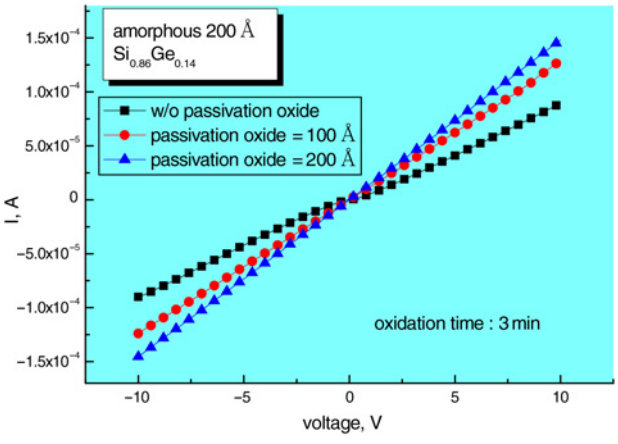

Figure 1 *Characterisation of the I–V curve of α-Si = 200 Å/$Si_{0.86}Ge_{0.14}$ nanowires*

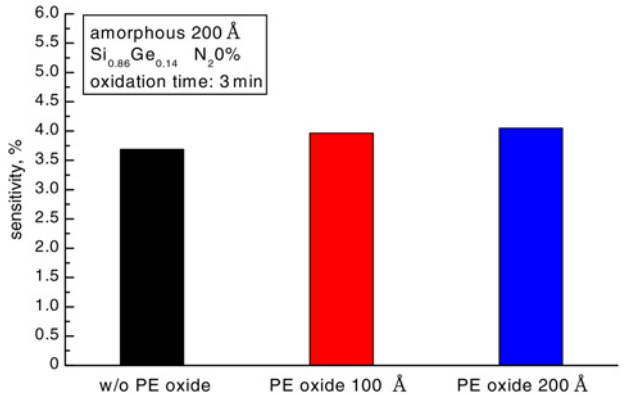

Figure 2 *Sensitivity of α-Si = 200 Å/$Si_{0.86}Ge_{0.14}$ nanowires after APTMS modification*

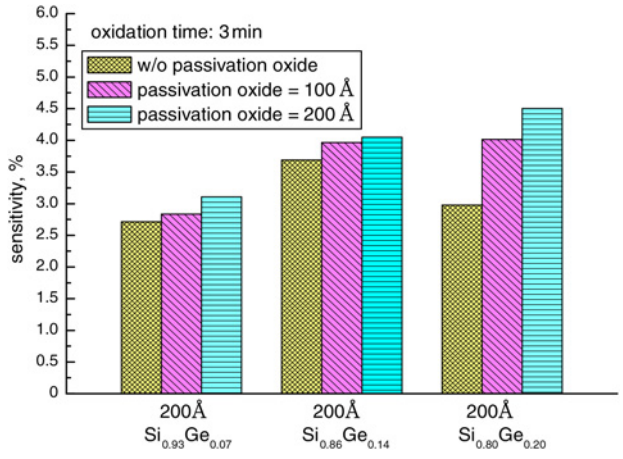

Figure 3 *Sensitivity of different Ge fraction nanowires with and without PECVD SiO_2 passivation*

doi: 10.1049/mnl.2012.0214

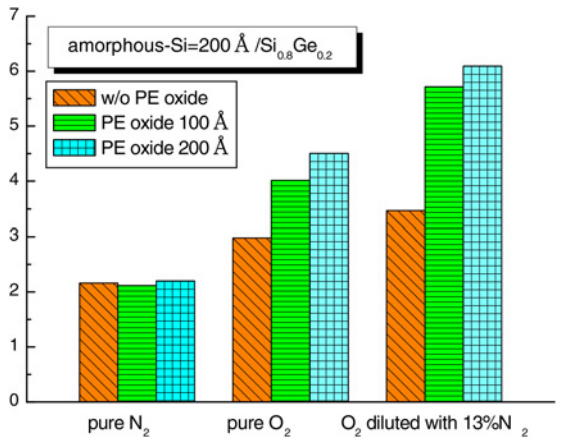

Figure 4 *Sensitivity of the $Si_{0.8}Ge_{0.2}$ nanowires with and without PECVD SiO_2 passivation under different ambient treatment*

surface defect rate. As these surface defects degraded the sensitivity of the SiGe nanowire, the oxidation rate could be reduced by using O_2 gas diluted with N_2 gas to prevent the formation of interface states during Ge condensation. Fig. 4 shows that the sensitivity of the nanowire in the 13% N_2 and O_2 gas mixture was higher than that of in pure N_2 or O_2 gas, even in the nanowire samples with no passivation layer. Fig. 5 displays the effect of oxidation duration on the $Si_{0.8}Ge_{0.2}$ nanowire under different passivation conditions. The sensitivity value peaked after 5 min of oxidation in the nanowire capped with PECVD oxide. The sensitivity improvement was ~1.3 times higher than that of the nanowire sample without a top passivation layer treated using the same oxidation duration. A degrading sensitivity was observed during prolonged oxidation of the nanowires with and without capping layers, since Ge not only piled up at the surface during the Ge condensation process, but also diffused into the buried oxide layer. The passage of O atoms through the thicker top oxide layer decreased as the oxidation time increased. Hence, both the Ge rejection rate and the Ge pile-up rate decreased, and the diffusion rate began to dominate the Ge distribution. Like a capping layer, the passivation layer suppresses oxidation. However, the major mechanism of the improved sensitivity is suppression of the unstable surface state caused by oxidation. The Ge condensation still occurs if the oxidation duration is suitable.

To clarify the influence of the oxidation rate on the sensitivity of the nanowire with a passivation layer, a poly-silicon nanowire was fabricated. Fig. 6 displays the effect of oxidation duration under different passivation conditions of the poly-silicon nanowire. The sensitivity of the poly-silicon nanowire without the SiO_2 passivation layer exceeded that of the nanowire with the layer, because

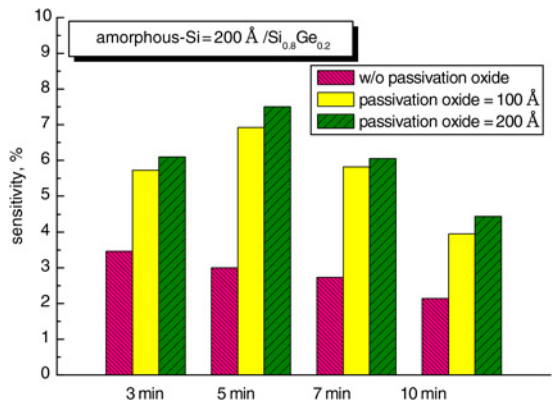

Figure 5 *Sensitivity of the $Sio_{0.8}Ge_{0.2}$* nanowire structure with different oxidation durations

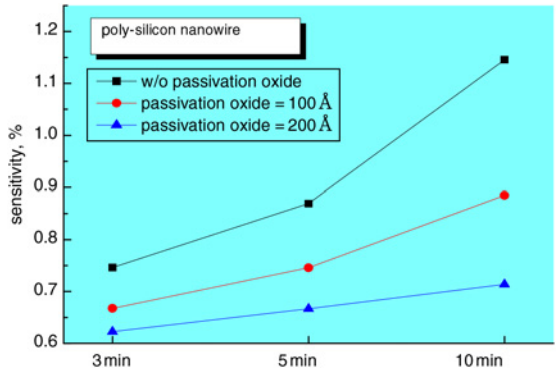

Figure 6 *Sensitivity of the poly-silicon nanowire structure with different oxidation duration*

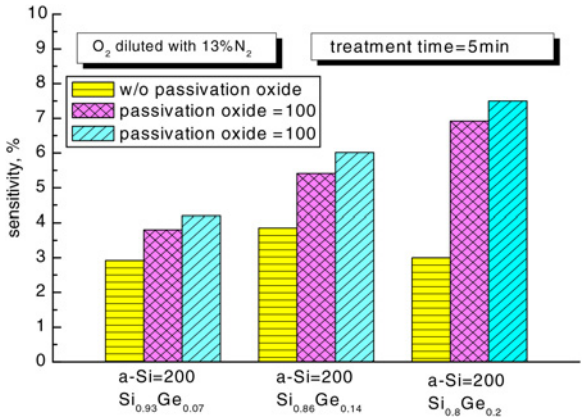

Figure 7 *Sensitivity results of SiGe nanowire with a 5 min oxidation duration with N_2 13% diluted O_2 gas treatment*

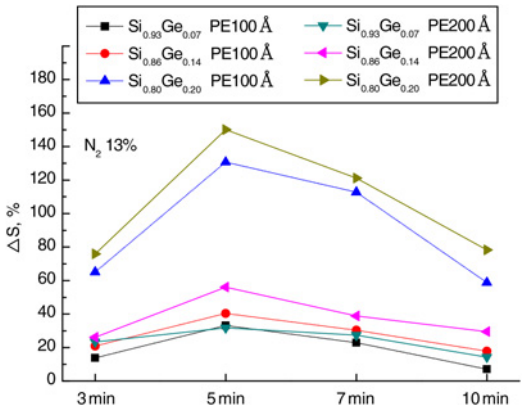

Figure 8 *Variation in sensitivity of $Si_{1-x}Ge_x$ nanowires under different oxidation duration and different PECVD oxide thickness with N_2 13% diluted O_2 gas treatment*

oxidation of the layer increased the surface-to-volume ratio of poly-silicon. The oxidation rate decreased as the thickness of the passivation layer increased, which reduced the surface-to-volume ratio and the sensitivity. Hence, this passivation oxide layer effectively reduced the oxidation rate and suppressed the instability of the surface state. Fig. 7 shows the sensitivity results for the SiGe nanowire samples with different Ge fractions after 5 min of oxidation. In this work, the greatest sensitivity improvement was achieved for the nanowire with a Ge fraction of 20%. Accordingly, the oxidation rate and the instability of the surface state were reduced by using a suitable capping layer, which

therefore increased the sensitivity of the SiGe nanowire with a high fraction of Ge. Finally, Fig. 8 displays the percentage variation in the sensitivity of the $Si_{1-x}Ge_x$ nanowires. The sensitivity variation was obtained by calculating the difference between $Si_{1-x}Ge_x$ nanowires with and without a capped passivation layer. The passivation layer had a higher efficiency in terms of improving the sensitivity of $Si_{0.8}Ge_{0.2}$ nanowires compared to $Si_{0.93}Ge_{0.07}$ and $Si_{0.93}Ge_{0.14}$ nanowires.

4. Conclusions: In this Letter, a PECVD SiO_2 passivation layer was used to reduce the surface state by reducing the oxidation rate to suppress formation of an interface at the SiGe surface by slowing oxidation rate under low temperatures. Hence, the sensitivity of a nanowire with a high Ge fraction can be improved by Ge condensation. Maximum improvement in the sensitivity of the $Si_{0.8}Ge_{0.2}$ nanowire was achieved with a 5 min oxidation duration and a 200 Å thick passivation oxide layer at 950°C. The maximum improvement in the sensitivity of the passivated nanowire was ~1.3 times higher than that of the nanowire without a passivation oxide layer.

5. Acknowledgments: The authors would like to thank the staff of the National Nano Device Laboratory for their technical help. They also acknowledge the financial support of the National Science Council (NSC) under contract nos. NSC 98-2221-E-009-174 MY3. The editorial assistance of Ted Knoy is appreciated.

6 References

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doi: 10.1049/mnl.2012.0214