

## **A SILICON-GERMANIUM NANOWIRE STRUCTURE AND A METHOD OF FORMING THE SAME**

### **FIELD OF THE INVENTION**

**[0001]** Embodiments of the invention relate to field of nanowire structures. By way of example, embodiments of the invention relate to a silicon-germanium (SiGe) nanowire structure arranged on a support substrate and a method of forming the same.

### **BACKGROUND OF THE INVENTION**

**[0002]** Nanowire transistors with gate fully surrounding the channel body have become promising device architectures to take the scaling to end-of-the-CMOS technology roadmap. One example involves fully complementary metal oxide semiconductor (CMOS) compatible Silicon-nanowire (SiNW) Gate-All-Around (GAA) n-channel metal-oxide-semiconductor field effect transistor (NMOSFET) and p-channel metal-oxide-semiconductor field effect transistor (PMOSFET) fabricated with nanowire channel in different crystal orientations and characterized at various temperatures down to 5K. SiNW width is controlled in 1 nm steps and varied from 3 to 6 nm. Devices show high drive current (2.4 mA/ $\mu$ m for NMOSFET, 1.3 mA/ $\mu$ m for PMOSFET), excellent gate control, and reduced sensitivity to temperature. Strong evidences of carrier confinement are noticed in terms of Id-Vg oscillations and shift in threshold voltage with SiNW diameter. Orientation impact has been investigated as well.

**[0003]** Another example involves both GAA and bulk devices and are shown operational on the same chip. GAA transistors have been realized with a minimal gate length of 50nm, with a conduction channel thickness of 20nm, an oxide thickness of 20A, and with an in-situ doped amorphous-Si as gate material. These transistors show a perfect immunity to short-channel effect (SCE)/Drain Induced

Barrier Lowering (DIBL) even without pockets implants. The bulk devices measured on the same chip were functional (allowing drive current of more than 600pNpm on 90nm devices) but have shown large SCE/DIBL up to 600mV and up to 1000mV on 90nm and 50nm devices, respectively.

[0004] Yet another example involves a nanowire FinFET structure developed for CMOS device scaling into the sub 10 nm regime. Accumulation mode P-FET and inversion mode N-FET with 5 nm and 10 nm physical gate lengths, respectively, are fabricated. N-FET gate delay (CV/I) of 0.22 ps and P-FET gate delay of 0.48 ps with excellent subthreshold characteristics are achieved, both with very low off leakage current less than 10 nA/ $\mu$ m. Nanowire FinFET device operation is also explored using 3-D full quantum mechanical simulation.

[0005] Nanowires are fabricated or synthesized by either top-down or bottom-up approaches. As there have been issues of controllability, placement and poor compatibility with standard Si-CMOS fabrication in relation to the bottom-up approach of fabrication, the top-down approach has taken the lead as a potential technology solution for future Si-CMOS.

[0006] An example of a top-down approach involves GAA Twin-Si-nanowire MOSFET (TSNWFET) with 15 nm gate length and 4 nm radius nanowires. The GAA TSNWFET demonstrated shows excellent short channel immunity. P-TSNWFET shows high driving current of 1.94 mA/ $\mu$ m while n-TSNWFET shows on-current of 1.44 mA/ $\mu$ m. Merits of TSNWFET and performance enhancement of p-TSNWFET have been explored using 3-D and quantum simulation.

[0007] Another example of a top-down approach involves a method for realizing arrays of vertically stacked laterally spread out nanowires using a fully Si-CMOS compatible process. The GAA MOSFET devices using these nanowire arrays show excellent performance in terms of near ideal sub-threshold slope (<70 mV/dec), high Ion/Ioff ratio (~107), and low leakage current. Vertical stacking economizes on

silicon estate and improves the on-state IDSAT at the same time. Both n- and p-FET devices have been demonstrated.

[0008] In addition to nanowire transistors, heterostructure transistors have also been proposed for high-speed CMOS circuits. One example involves a new generation of high-speed heterostructure devices compatible with a modified Modulation-Doped Field Effect Transistor (MODFET). These devices include a modified MODFET with a buried p-channel, a variable threshold voltage MODFET, a lateral n-p-n bipolar transistor, and a three-terminal planar photodetector. These devices can be integrated together and with an optical waveguide. The MODFET has high speed, high collection efficiency, and it may operate in either p-i-n mode with low noise or the avalanche mode with high gain. The gate terminal allows modulation of the photodetector output.

[0009] Further, based on the principle of high injection velocity heterojunction bipolar transistor (HBT), a planar MOSFET structure with a heterojunction source structure has been demonstrated. It involves a source-heterojunction-MOS-transistor (SHOT), which is a novel high-speed MOSFET with relaxed-SiGe/strained-Si heterojunction source structures for quasi-ballistic or full-ballistic transistors. Using the band-offset energy at the source SiGe/strained-Si heterojunction, high velocity electrons can be injected into the strained-Si channel from the SiGe source region. The publication experimentally demonstrated that the transconductance is enhanced in SHOT for high applied drain voltage, compared to that of strained- and conventional silicon-on-insulator (SOI) MOSFETs. The publication also shows that the transconductance enhancement in SHOT depends on both the gate drive and the drain bias.

[0010] However, there is still a need for a transistor with better channel mobility and higher current.

## SUMMARY OF THE INVENTION

[0011] In one embodiment of the invention, a silicon-germanium nanowire structure arranged on a support substrate is provided. The method includes at least one germanium-containing supporting portion arranged on the support substrate, at least one germanium-containing nanowire disposed above the support substrate and arranged adjacent the at least one germanium-containing supporting portion, wherein germanium concentration of the at least one germanium-containing nanowire is higher than the at least one germanium-containing supporting portion.

[0012] In another embodiment of the invention, a transistor comprising the silicon-germanium nanowire structure arranged on a support substrate is provided. The transistor further includes a tunneling layer around the at least one germanium-containing nanowire and a gate region positioned over the tunneling layer.

[0013] In another embodiment of the invention, a method of forming a silicon-germanium nanowire structure arranged on a support substrate is disclosed. The method includes forming at least one germanium-containing supporting portion on the support substrate, forming at least one germanium-containing nanowire above the support substrate and adjacent the at least one germanium-containing supporting portion, wherein germanium concentration of the at least one germanium-containing nanowire is higher than the at least one germanium-containing supporting portion.

[0014] In a further embodiment of the invention, a method of forming a transistor comprising forming the silicon-germanium nanowire structure arranged on a support substrate is disclosed. The method further includes forming a tunneling layer around the at least one germanium-containing nanowire and forming a gate region positioned over the tunneling layer.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0015] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0016] **FIG. 1** shows a cross-sectional view of a silicon-germanium nanowire (SGNW) transistor in accordance with an embodiment of the invention;

[0017] **FIG. 2** shows a band diagram corresponding to a cross-sectional view of a SGNW transistor in accordance with an embodiment of the invention;

[0018] **FIG. 3A** to **FIG. 3H** show a process flow of a method of forming a SGNW transistor in accordance with an embodiment of the invention;

[0019] **FIG. 4A** show a cross-sectional view along plane AA' of the SGNW transistor in **FIG. 3E** after fin patterning and before second Ge condensation in accordance with an embodiment of the present invention; **FIG. 4B** show a cross-sectional view along plane AA' of the SGNW transistor in **FIG. 3E** after fin patterning and after second Ge condensation in accordance with an embodiment of the present invention;

[0020] **FIG. 5A** and **FIG. 5B** show cross-sectional views along planes AA' and BB' of the SGNW transistor in **FIG. 3F** in accordance with an embodiment of the invention;

[0021] **FIG. 6A** and **FIG. 6B** show respective cross-sectional views along plane AA' of the SGNW transistor in **FIG. 3G** with the resultant structure being a MOSFET or a Silicon-Oxide-Nitride-Oxide-Silicon (SONOS) memory device in accordance with an embodiment of the invention;

[0022] FIG. 7 shows a flow chart of a method of forming a SGNW transistor in accordance with an embodiment of the invention;

[0023] FIG. 8A shows a scanning electron microscopy (SEM) image of a SGNW structure taken after a second Ge condensation process in accordance with an embodiment of the invention; FIG. 8B shows a SEM image of a SGNW structure after gate pattern transfer in accordance with an embodiment of the invention; FIG. 8C shows a cross-sectional High Resolution Transmission Electron Microscopy (HRTEM) image of a SGNW in accordance with an embodiment of the invention;

[0024] FIG. 9A shows a SEM image of a SGNW structure after nanowire release in accordance with an embodiment of the invention; FIG. 9B shows a SEM image of a SGNW structure after nanowire release taken with about 45 degree rotation in accordance with an embodiment of the invention;

[0025] FIG. 10A shows a TEM image of a SGNW GAA FET with  $\text{HfO}_2/\text{TaN}$  gate in accordance with an embodiment of the invention; FIG. 10B shows a magnified image of a near-circular SGNW in accordance with an embodiment of the invention; FIG. 10C shows a reciprocal space diffractogram showing a lattice structure inside the SGNW in accordance with an embodiment of the invention;

[0026] FIG. 11 shows a normalized  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with gate length ( $L_g$ ) of approximately 350 nm in accordance with an embodiment of the invention;

[0027] FIG. 12 shows a transconductance ( $g_m$ ) vs gate voltage ( $V_G$ ) characteristic plot of a SGNW PMOSFET and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention;

[0028] FIG. 13 shows a drive current ( $I_{Dsat}$ ) vs temperature characteristic plot of a SGNW PMOSFET and a  $Si_{0.7}Ge_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention;

[0029] FIG. 14 shows a threshold voltage ( $V_T$ ) vs temperature characteristics plot of a SGNW PMOSFET and a  $Si_{0.7}Ge_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention;

[0030] FIG. 15 shows a  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $L_g$  of 500 nm in accordance with an embodiment of the invention;

[0031] FIG. 16 shows a  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET with  $L_g$  of 500 nm in accordance with an embodiment of the invention;

[0032] FIG. 17 shows a  $g_m$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $L_g$  of 500 nm in accordance with an embodiment of the invention;

[0033] FIG. 18 shows a resistance vs  $V_G$  characteristics plot of a SGNW PMOSFET at strong inversion with low  $V_D$  in accordance with an embodiment of the invention;

[0034] FIG. 19 shows a  $V_T$  vs temperature characteristics plot of SGNW PMOSFET with respective gate lengths of 350 nm, 400 nm and 500 nm in accordance with an embodiment of the invention;

[0035] FIG. 20 shows a linear  $g_m$  peak vs temperature characteristics plot of SGNW PMOSFET with respective gate lengths of 350 nm, 400 nm and 500 nm in accordance with an embodiment of the invention;

[0036] FIG. 21 shows a  $I_{ON}$  vs  $I_{OFF}$  characteristics plot of SGNW PMOSFET with respective radii of 6 nm and 8 nm in accordance with an embodiment of the invention;

[0037] FIG. 22 shows a  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $\langle 100 \rangle$  channel direction in accordance with an embodiment of the invention;

[0038] FIG. 23 shows a  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET with  $\langle 100 \rangle$  channel direction in accordance with an embodiment of the invention;

[0039] FIG. 24 shows a  $I_D$  vs  $V_G$  characteristics plot of a unpassivated SGNW NMOSFET in accordance with an embodiment of the invention;

[0040] FIG. 25 shows a  $I_D$  vs  $V_D$  characteristics plot of a unpassivated SGNW NMOSFET in accordance with an embodiment of the invention;

[0041] FIG. 26 shows a  $V_{OUT}$  vs  $V_{IN}$  characteristics plot of a CMOS inverter incorporating a SGNW structure in accordance with an embodiment of the invention;

## DESCRIPTION

[0042] Exemplary embodiments of a silicon-germanium nanowire structure on a support substrate, and a method of forming the same are described in details below with reference to the accompanying figures. In addition, the exemplary embodiments described below can be modified in various aspects without changing the essence of the invention.

[0043] FIG. 1 shows a cross-sectional view of a SGNW transistor 102 in accordance with an embodiment of the invention. The SGNW transistor 102 includes a support substrate 104, a buried oxide (BOX) layer 106, a bottom gate electrode 108, a top gate electrode 110, a source region 112, a nanowire channel region 148

and a drain region 116. The bottom gate electrode 108 is separated from the source region 112, the nanowire channel region 148 and the drain region 116 by a bottom gate dielectric layer 118 and the top gate electrode 110 is separated from the source region 112, the nanowire channel region 148 and the drain region 116 by a top gate dielectric layer 120. The bottom gate electrode 108 and the top gate electrode 110 may be separate electrodes or may be a single electrode surrounding the nanowire channel region 148. Similarly the bottom gate dielectric layer 118 and the top gate dielectric layer 120 may be separate dielectric layers or a single dielectric layer surrounding the nanowire channel region 148.

[0044] The support substrate 104 may be formed from any suitable semiconductor materials including, but not limited to Si, sapphire, poly-silicon, silicon oxide ( $\text{SiO}_2$ ) or silicon nitride ( $\text{Si}_3\text{N}_4$ ). The BOX layer 106 is usually an insulating layer. The BOX layer 106 is typically silicon oxide ( $\text{SiO}_2$ ) but may be formed from any suitable insulating materials including, but not limited to tetraethylorthosilicate (TEOS), silane ( $\text{SiH}_4$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ) or silicon carbide ( $\text{SiC}$ ). The thickness of the BOX layer 106 may range from about 1kÅ to about a few  $\mu\text{m}$  but is not so limited. The top 120 and bottom gate dielectric layer 118 can be any suitable dielectric, for example silicon nitride ( $\text{Si}_3\text{N}_4$ ,  $\text{SiN}_x$ ), Magnesium Oxide ( $\text{MgO}$ ) or Scandium Oxide ( $\text{Sc}_2\text{O}_3$ ), typically  $\text{SiO}_2$  but not so limited. The source region 112, the drain region 116 and the nanowire channel region 148 may be formed of SiGe. The bottom gate electrode 108 and the top gate electrode 110 may be Si, poly-silicon (poly-Si), amorphous silicon, metals such as tantalum nitride ( $\text{TaN}$ ), titanium nitride ( $\text{TiN}$ ), hafnium nitride ( $\text{HfN}$ ), aluminum (Al) and tungsten (W) but not so limited.

[0045] The Ge concentration in the nanowire channel region 148 is higher than that in the source region 112 or in the drain region 116. The difference in Ge concentration results in the formation of a heterojunction 122 at the respective interface between the source region 112 and the nanowire channel region 148 and between the drain region 116 and the nanowire channel region 148. The Ge

concentration in the nanowire channel region **148** is typically in the range of about 50% to 90%, preferably about 70%. The Ge concentration in the respective source region **112** or drain region **116** is typically about 10% to 50%, preferably about 30%. The higher the Ge concentration in the nanowire channel region **148**, the higher the channel mobility. For a SiGe substrate, the higher the Ge content, the higher the carrier mobility for carrier inside such channel. This applies to both electrons and holes.

[0046] **FIG. 2** shows a band diagram corresponding to a cross-sectional view of a SGNW transistor **102** in accordance with an embodiment of the invention. The band diagram **124** shows the respective valence band energy value ( $E_V$ ) and conduction band energy value ( $E_C$ ) of the source region **112**, the SGNW channel region **148** and the drain region **116**. From the difference in  $E_V$  and  $E_C$  between the source region **112** and the SGNW channel region **148** and between the SGNW channel region **148** and the drain region **116**, it can be inferred that two respective heterojunctions **122** are formed. One of the heterojunction **122** is formed at the interface between the source region **112** and the SGNW channel region **148** and the other heterojunction **122** is formed at the interface between the drain region **116** and the SGNW channel region **148**.

[0047] With higher Ge concentration in the SGNW channel region **148**, the band gap of the SGNW channel region **148** decreases significantly as given by  $E_g(\text{alloy}) = x E_{g1} + (1-x) E_{g2}$ , with  $x$  being the Ge fraction in the SGNW channel region **148** and  $E_{g1}$ ,  $E_{g2}$  being the band gaps of Ge and Si respectively. As an illustration, with about 30% Ge concentration in the respective source region **112** and drain region **116** and about 70% Ge concentration in the channel region **148**, the band gap  $E_g$  or energy difference between the  $E_C$  and the  $E_V$  in the respective source region **112** and drain region **116** is about 0.99 electron volts (eV) and the band gap in the channel region **148** is about 0.81eV without considering the strain effect in the SGNW channel **148**. This results in a valence band offset  $\Delta E_V$  or energy difference between the valence

band  $E_v$  values in the channel region 148 and the source region 112 of about 0.15eV. Hole injection velocity may increase with a higher valence band offset  $\Delta E_v$ .

[0048] FIG. 3A to 3H show a process flow of a method of forming a SGNW transistor in accordance with an embodiment of the invention. The method starts with a starting substrate 126 in FIG. 3A. The starting substrate 126 can be a Silicon-On-Insulator (SOI) substrate, a bulk silicon substrate, or other relevant substrates depending on the application. The SOI substrate 126 is used as an illustration in FIG. 3A. The SOI substrate 126 includes a semiconductor device layer 128 separated vertically from a support substrate 104 by an insulating layer or a buried oxide (BOX) layer 106. The BOX layer 106 electrically isolates the semiconductor device layer 128 from the support substrate 104. The SOI substrate 126 may be fabricated by any standard techniques, such as wafer bonding or a separation by implantation of oxygen (SIMOX) technique.

[0049] In the illustrated embodiment of the invention in FIG. 3A, the semiconductor device layer 128 is typically Si but may be formed from any suitable semiconductor materials including, but not limited to poly-silicon (poly-Si), gallium arsenide (GaAs), germanium (Ge) or silicon-germanium (SiGe). The thickness of the semiconductor device layer 128 may range from about 50 nm to about 90 nm, typically about 70 nm but is not so limited. The support substrate 104 is typically Si but may be formed from any suitable semiconductor materials including, but not limited to sapphire, poly-silicon, silicon oxide ( $\text{SiO}_2$ ) or silicon nitride ( $\text{Si}_3\text{N}_4$ ). In this regard, an SOI substrate can also be considered as a support substrate 104. The BOX layer 106 is usually an insulating layer. The BOX layer 106 is typically  $\text{SiO}_2$  but may be formed from any suitable insulating materials including, but not limited to tetraethylorthosilicate (TEOS), silane ( $\text{SiH}_4$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ) or silicon carbide (SiC). The thickness of the BOX layer 106 may range from about 1  $\mu\text{m}$  to about a few  $\mu\text{m}$  but is not so limited.

[0050] In FIG. 3A, prior to any deposition, the Si device layer 128 may be thinned down to a range between about 10 nm to about 40 nm, typically about 25 nm thick by oxidation. The oxidation may be a wet oxidation (done in H<sub>2</sub>O vapor) or dry oxidation (done in O<sub>2</sub> gas) or any other suitable techniques. The thinning of the Si device layer 128 is an optional step and the purpose of the thinning is so as to maintain the resultant FinFET height, which is a result of a combination of the thickness of the Si device layer 128 and the thickness of the subsequent SiGe layer. To maintain the resultant FinFET height within a desired height, the Si device layer 128 may be thinned so that a thicker SiGe layer may be deposited subsequently, thereby allowing higher Ge content film formation. A thicker SiGe layer and a thinner Si device layer 128 will give rise to a higher Ge content SGNW in the resultant structure.

[0051] After the thinning step, a surface clean step may be carried out with RCA and hydrogen fluoride (HF). This surface clean step is carried out because contaminants present on the surface of the Si device layer 128 at the start of processing, or accumulated during processing, have to be removed at specific processing steps in order to obtain high performance and high reliability semiconductor devices, and to prevent contamination of process equipment, especially the high temperature oxidation, diffusion, and deposition tubes or chambers. The RCA clean is the industry standard for removing contaminants from substrates or wafers. The RCA cleaning procedure usually has three major steps used sequentially: Organic Clean (for example removal of insoluble organic contaminants with a 5:1:1 H<sub>2</sub>O:H<sub>2</sub>O<sub>2</sub>:NH<sub>4</sub>OH solution), Oxide Strip (for example removal of a thin silicon dioxide layer using a diluted 50:1 dionized-water H<sub>2</sub>O:HF solution) and metallic Ion Clean (for example removal metal atomic contaminants using a solution of 6:1:1 H<sub>2</sub>O:H<sub>2</sub>O<sub>2</sub>: HCl). Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) mixed with Hydrogen Peroxide (H<sub>2</sub>O<sub>2</sub>) clean may also be used. Other types of cleaning solutions or steps may also be used.

[0052] After the surface clean step, a starting SiGe epitaxial layer 130 with uniform Ge content in the range of about 15 % to about 25 % may be grown on the Si device layer 128 as shown in FIG. 3B. The SiGe layer 130 may be grown using a cold wall Ultra High Vacuum Chemical Vapor Deposition (UHVCVD) reactor at a temperature from about 500°C to about 600°C, typically about 580°C but not so limited, with a combination of SiH<sub>4</sub> and germane (GeH<sub>4</sub>) gases. The thickness of the SiGe layer 130 is between about 30nm to about 60nm but is not so limited. Alternatively, a plurality of alternate layers of SiGe and Si may also be grown on the Si device layer 128 to form a resultant stacked nanowire structure. In this example, Si will be deposited by SiH<sub>4</sub> gas only. GeH<sub>4</sub> turn-off or turn-on during different film deposition cycles may be used to induce the respective Si, SiGe layers. In addition, different SiGe films may be obtained by varying the GeH<sub>4</sub>, SiH<sub>4</sub> flow ratio. Temperature may also be in the range of about 500°C to about 600°C for this type of UHVCVD configuration.

[0053] An optional Si capping layer (not shown) may also be deposited on the SiGe layer 130. The Si capping layer serves as a sacrificial layer during the gate dielectric or oxide formation, and also during the passivation to SiGe to prevent Ge exposure. The oxidation process will consume the top Si capping layer but not the SiGe layer as the oxide quality on this SiGe surface is typically inferior when compared to that of oxide interfaced with Si.

[0054] After the growth of the SiGe epitaxial layer 130 and optional deposition of the Si capping layer, a first Ge condensation process and a cyclic annealing step may be carried out. Ge condensation may be achieved by thermal oxidation of the SiGe layer whereby Si oxidizes faster when compared to Ge, and the Ge atoms are rejected from the SiO<sub>2</sub> layer into the SiGe layer below. The Ge diffusion and accumulation are dependent on the thermal environment and vary with gas flow and temperature. Higher Ge-content SiGe layer can be obtained when subjected to a longer oxidation period.

[0055] FIG. 3C shows a resultant structure 136 after the first Ge condensation and the cyclic annealing step. The resultant structure 136 includes an oxidized layer ( $\text{SiO}_2$  layer 132) on a resultant SiGe layer 134, with the resultant SiGe layer 134 arranged on the BOX layer 106. The Ge atoms are rejected from the  $\text{SiO}_2$  layer 132 into the SiGe layer 134 below. The cyclic annealing step may be carried out at temperatures of about  $750^\circ$  to about  $950^\circ$  but not so limited. The cyclic annealing step is carried out so as to reduce any defects, and also to distribute the Ge evenly across the SiGe layer 134 dynamically.

[0056] After the first Ge condensation process, the  $\text{SiO}_2$  layer 132 may be etched away using a suitable etchant for example dilute hydrofluoric acid (DHF) (1:200). FIG. 3D shows the resultant SiGe layer 134 on the BOX layer 106 after the etching process, forming a structure termed SiGe on insulator (SGOI) 138. The thickness of the resultant SiGe layer 134 is about 20 nm to 30 nm but is not so limited. The Ge percentage and the resultant SiGe layer 134 thickness are respectively determined by the thickness of the Si device layer 128, the thickness of the starting SiGe layer 130 and the Ge condensation time for example.

[0057] Next, a relatively thin liner oxide layer or pad oxide layer (not shown) is deposited on the resultant SiGe layer 134. The purpose of the thin liner oxide layer is to protect the SiGe layer 134 from any subsequent deposited layers (e.g. silicon nitride (SiN) hard mask layer). For example, the liner oxide layer prevents exposure of the resultant SiGe layer 134, where the surface may be oxidized easily and unevenly. Subsequently, a SiN hard mask layer (not shown) is deposited on top of the thin liner oxide layer. Other examples of hard mask include a combination of SiN and  $\text{SiO}_2$  stacks. Then a photoresist layer (not shown) is applied or coated onto a top surface of the SiN hard mask layer. The photoresist layer is then patterned to form a fin structure including a fin portion arranged in between two supporting portions by standard photolithography techniques, for example 248 nm krypton fluoride (KrF) lithography. Alternating-Phase-Shift mask (Alt-PSM) may be used to pattern the narrow fin portion which may have a width of about 40 nm to about 200 nm but is

not so limited. Subsequently, using the patterned photoresist layer as a mask, portions of the SiN, the liner oxide layer and the SiGe layers 134 not covered by the mask may be etched away by a suitable etching process such as a dry etching process for example reactive-ion-etching (RIE) in Sulfur Hexafluoride (SF<sub>6</sub>).

[0058] In FIG. 3E, a resultant fin structure 140 comprising of a fin portion 142 arranged in between and connected at each end to a respective supporting portion 144 is formed on the BOX layer 106. The fin portion 142 acts as a bridge linking the respective supporting portions 144. The supporting portions 144 are typically blocks with a wider dimension when compared to the fin portion 142. FIG. 3E shows that the fin portion 142 is arranged in the middle between the two supporting portions 144. Alternatively, the fin portion 142 can also be arranged towards either side of the two supporting portions 144. The fin portion 144 has a width (denoted by "w") of about 40 nm to about 200 nm, but not so limited. With height (denoted by "h") typically from about 1 kÅ to about 2 kÅ, the ratio of height to width in such fin portion 142 may range from 5:1 to 1:2, but not so limited.

[0059] After forming the fin structure 140, the photoresist layer is removed or stripped away by a photoresist stripper (PRS). Photoresist stripping, or simply 'resist stripping', is the removal of unwanted photoresist layer. Its objective is to eliminate the photoresist material as quickly as possible, without allowing any surface material under the photoresist to be attacked by the chemicals used. In this regard, any other suitable techniques or processes may also be used in order to provide greater flexibility with respect to forming of the fin structure comprising the fin portion arranged in between two supporting portions on the BOX layer.

[0060] The fin structure 140 is then subjected to a second Ge condensation process at a temperature of about 875 degree and for about 10 minutes, but not so limited. In FIG. 3F, the second Ge condensation step resulted in the formation of a SGNW structure 146 including an oxide-encapsulated Ge-rich SGNW channel 148

connected on both sides to lower Ge-content supporting portions 150. The diameter of the resultant SGNW channel 148 is between 7 nm to 13 nm but not so limited.

[0061] During this second Ge condensation, a pattern size and shape dependent Ge condensation takes place. The second Ge condensation is a process which converts the fin structure 140 from a homogeneous structure (homostucture) to a heterostructure. In the narrower fin portion 142, the second condensation proceeds 2-dimensionally (almost from all 4 sides) as opposed to 1-dimensionally in the larger supporting portions 144 (only from the top). Ge atoms diffused from the top and side surfaces into the center of the fin portion 142, further enriching the Ge concentration, and simultaneously reducing cross-sectional dimensions of the fin portion 142. This resulted in Ge enrichment within the resultant SGNW channel 148, along with size reduction of the fin portion 142 from a range between about 40 nm to about 200 nm to the resultant SGNW channel 148 diameter of between about 7 nm to about 13 nm. The supporting portions 144 maintained almost the same Ge concentration as obtained by the first Ge condensation.

[0062] Subsequently, cyclic annealing is performed before the SiN mask layer may be washed away by phosphoric acid ( $\text{H}_3\text{PO}_4$  for example). Cyclic annealing before oxide removal is helpful to prevent breakage in the SGNW 148, possibly due to stress relief or redistribution in the SGNW 148. Then the hard mask is being etched away. The thin liner oxide layer and the  $\text{SiO}_2$  layer 153 surrounding the SGNW 148 is also etched using dilute hydrofluoric acid (DHF) (1:200) to release the SGNW 148. Any other suitable etchant can also be used to release the SGNW 120. The dimension of each SGNW 148 is about 7 nm to 13 nm but not so limited. The diameter of each SGNW 148 may be determined by the initial layer deposition and oxidation cycles. The result is a SGNW channel 148 supported on both ends by the respective supporting portions 150 after the second Ge condensation on the BOX layer 106 as shown in Fig. 3F. The ratio of the width of the respective supporting portions 150 and the diameter of the SGNW 148 may be greater than a range between about 2 to about 20, typically about 10.

[0063] Subsequently, the nanowire release may be followed by a surface passivation step where the surface of the SGNW 148 is passivated with about 2 nm but not so limited of epitaxial Si layer (not shown). The passivation layer serves as a sacrificial layer. The oxidation process consumes the passivation layer before the oxidants reach to the channel surface, which is the SGNW 148. This allows for the oxide and channel interface to be maintained within the Si passivation layer instead of into the SGNW 148. This is followed by an oxide growth (not shown) with a resultant oxide thickness of about 4 nm to 8 nm but not so limited forming the gate dielectric. The oxide may be grown by a dry oxidation process at a temperature of between about 800° to about 900° or by a CVD process. The gate dielectric may be any suitable dielectric for example SiO<sub>2</sub>, SiN<sub>x</sub>, MgO or Sc<sub>2</sub>O<sub>3</sub>.

[0064] Next in FIG. 3G, a conductive layer (not shown) of about 1300 Angstrom thick is deposited over the oxide layer by low power physical vapor deposition (PVD). The conductive layer may be silicon, poly-silicon, amorphous silicon, metals such as tantalum nitride (TaN), titanium nitride (TiN), hafnium nitride (HfN), aluminum (Al) and tungsten (W) but not so limited. This is followed by patterning and etching of the conductive layer to form the gate electrode 152. The gate length is about 75 nm but not so limited. The gate electrode 152 can be deposited as intrinsically undoped, having different doping based on the doping methods or as metal gates.

[0065] Subsequently in FIG. 3H, the supporting regions 144 of the fin structure 140 may be implanted with a p-type dopant or a n-type dopant to form the respective source 112 and drain regions 116 and the gate electrode 152 may be implanted with a dopant of opposite conductivity to that of the supporting regions 144 of the fin structure 140. To realize SGNW PMOSFET, p-type dopants for example BF<sub>2</sub> with a dose of about  $4 \times 10^{15} \text{ cm}^{-2}$  at about 35 keV may be implanted into the supporting regions 144 to form the respective source region 112 and the drain region 116. Any other suitable p-type dopant such as aluminum, gallium and indium may also be used. An N-type dopant for example Arsenic (As) with a dose of about  $4 \times 10^{15} \text{ cm}^{-2}$

at about 30 keV may be implanted into the gate electrode **152**. The gate **152** and source **112** or drain **116** may be implanted at the same time. Any other suitable n-type dopants such as phosphorous (P), antimony (Sb), bismuth (Bi) may also be used. Incidentally, the nanowires are without any intentional doping and the combination of gate electrode **152** types and dopants adopted for the source **112** or drain **116** implant define whether the transistor will be a p-channel MOSFET (PMOSFET) or an n-channel MOSFET (NMOSFET).

[0066] After the respective dopant implants, a source **112**, drain **116** and gate **152** activation anneal step at a temperature of approximately 875° for 15 minutes may be carried out to ensure uniform diffusion of dopants in the source **112**, drain **116** and gate **152** regions. The process of forming the SGNW MOSFET **102** may be completed by the standard metal contact formation and sintering steps.

[0067] FIG. 4A show a cross-sectional view along plane AA' of the SGNW transistor in FIG. 3E after fin patterning and before second Ge condensation in accordance with an embodiment of the present invention. FIG. 4A shows a SiGe fin portion **142** disposed on the BOX layer **106**. The BOX layer **106** is further arranged on the support substrate **104**.

[0068] FIG. 4B show a cross-sectional view along plane AA' of the SGNW transistor in FIG. 3E after fin patterning and after second Ge condensation in accordance with an embodiment of the present invention. In FIG. 4B, the SiGe fin portion **142** is oxidized resulting in a SGNW **148** surrounded by a layer of SiO<sub>2</sub> layer **153**. The SGNW **148** surrounded by the SiO<sub>2</sub> layer **153** is disposed on the BOX layer **106** and the BOX layer **106** is further arranged on the support substrate **104**.

[0069] FIG. 5A and FIG. 5B show cross-sectional views along planes AA' and BB' of the SGNW transistor **102** in FIG. 3F in accordance with an embodiment of the invention. FIG. 5A shows that the Ge concentration of the SGNW **148** is about 70 % and the diameter (denoted by "d") of the SGNW **148** may be a range between

about 7 nm to about 13 nm. **FIG. 5B** shows the Ge concentration of the respective SiGe source **112** or drain region **116** is about 30 % and the width (denoted by “w”) of the respective SiGe source **112** or drain region **116** is about 1  $\mu\text{m}$  but not so limited. The width of the SiGe source **112** or drain region **116** is substantially larger than the diameter of the SGNW **148** so that the oxidation is effected mainly in the fin portion **142**.

[0070] **FIG. 6A** and **FIG. 6B** show respective cross-sectional views along plane AA' of the SGNW transistor in **FIG. 3G** with the resultant structure being a MOSFET or a SONOS memory device in accordance with an embodiment of the invention. **FIG. 6A** shows a cross-sectional view with the resultant structure of a MOSFET. To form the MOSFET, the SGNW channel **148** is surrounded by a tunneling oxide layer **154** and is subsequently surrounded by a gate region **152**. The tunneling oxide layer **154** is a dielectric layer and the dielectric layer **154** may be  $\text{SiO}_2$ ,  $\text{HfO}_2$ ,  $\text{SiN}_x$ ,  $\text{MgO}$  or  $\text{Sc}_2\text{O}_3$  but not so limited. The gate region or gate layer **152** may be tantalum nitride (TaN), titanium nitride (TiN), typically poly-Si, but not so limited. The thickness of the gate region **152** is about 1 kÅ to about 2 kÅ and the thickness of the dielectric layer **154** is about 45 Å.

[0071] **FIG. 6B** shows a cross-sectional view with the resultant structure of a SONOS memory device. To form the SONOS, the SGNW **148** is surrounded by a tunneling oxide layer **154** and a charge trapping structure **158** is positioned over the tunneling oxide layer **154**. A blocking oxide layer **160** is further positioned over the charge trapping structure **158** and the blocking oxide layer **160** is surrounded by a gate region **152**. For the SONOS, the tunneling oxide layer **154** surrounding the SGNW channel **148** is a dielectric layer and the blocking oxide layer **160** surrounding the charge trapping structure **158** is also a dielectric layer. The dielectric layer is typically  $\text{SiO}_2$  but not so limited. The charge trapping structure **158** may include any one or more of a group of high dielectric materials, for example silicon nitride ( $\text{Si}_3\text{N}_4$ ), hafnium dioxide ( $\text{HfO}_2$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ) but not so limited. The tunneling oxide layer **154** is typically about 45Å thick, the charge trapping

structure 158 is typically about 45Å thick and the blocking oxide layer 160 is typically about 80Å thick, but not so limited. The SGNW channel 148 may be used in all non-volatile applications.

[0072] FIG. 7 shows a flow chart of a method of forming a SGNW transistor in accordance with an embodiment of the invention. The method 700 begins at 702 with a starting SOI substrate 126 comprising a Si device layer 128 separated vertically from a support substrate 104 by a BOX layer 106. Next, in 704 a layer of SiGe 130 is grown on the Si device layer 128 of the SOI substrate 126. An optional Si capping layer may be deposited on the SiGe layer 130. In 706, a first Ge condensation step is carried out to convert the SiGe layer 130 on the Si device layer 128 into a SiO<sub>2</sub> layer 132 on a SiGe layer 134, forming a SGOI 138. This is followed by cyclic annealing. Next in 708, the SiO<sub>2</sub> layer 132 is stripped away using a suitable etchant. In step 710, an optional pad oxide layer is deposited on the SiGe layer 134. This is followed by a SiN hard mask deposition on the pad oxide layer. Then, a photoresist layer is coated onto the SiN hard mask layer. The photoresist layer is then patterned to form a fin structure including a fin portion arranged in between two supporting portions by standard photolithography techniques. Using the fin pattern photoresist layer as a mask, portions of the SiN, pad oxide layer and SiGe layer 134 not covered by the mask are etched away to realize a fin structure 140 comprising of a fin portion 142 arranged in between two supporting portions 144 on the BOX layer 106. In 712, the fin structure 140 is further subjected to a second Ge condensation process to achieve a nanowire structure 146 with a SGNW 148 being surrounded by a layer of oxide 153. Subsequently, the nanowire structure 146 is subject to an annealing step to repair the crystal defects. Next, the oxide layer 150 surrounding the SiGe supporting portions 144 and the oxide layer 153 surrounding the SGNW 148 are etched. Removal of the SiO<sub>2</sub> layer 153 surrounding the SiGe core 148 releases the SGNW 148 thereby forming the resultant SiGe nanowire structure. In 714, a Si passivation layer is grown on the SGNW 148, followed by deposition of a gate dielectric layer on the Si passivation layer. In 716, a conductive layer is deposited, followed by gate patterning and etching to form the gate electrode 152. In 718, the

supporting portions 144 are doped to form the source 112 and drain regions 116 of the respective SGNW MOSFET 102. The gate electrode 152 may also be doped with a different dopant from that of the resultant source 112 and drain 116 regions. This is followed by an annealing step to ensure uniform diffusion of dopants in the source 112, gate 152 and drain 116 regions. In 720, the method of forming a SGNW MOSFET 102 may be completed with the standard pre-metal dielectric deposition, metal contact formation and sintering steps.

### **Results**

[0073] **FIG. 8A** shows a SEM image of a SGNW structure taken after a second Ge condensation process in accordance with an embodiment of the invention. **FIG. 8A** shows a SGNW channel 148 arranged between respective source 112 and drain 116 extension pads. The Ge concentration in the SGNW channel region 148 is about 70% and the Ge concentration in the respective source 112 or drain 116 extension pads is about 30%, thereby forming a heterojunction 122. In **FIG. 8A**, the gate edge is sitting on the wider curved extensions of the nanowires (corner rounding effect in lithography). Being wide, the curved extension has a much lower Ge concentration compared to the nanowire channel 148. The heterojunction 122 is formed under the gate region 152, thereby fulfilling the requirement for the formation of a heterojunction MOSFET. Since pattern-dependent Ge condensation is employed, the heterojunction 122 will not be abrupt. A non-abrupt heterojunction can result in enhanced carrier injection velocity and further help to reduce the energy carrier spike at the source heterojunction 122. In pattern dependent Ge condensation, pattern abruptness (radii of curvature of the curved extensions) can be used to tune the abruptness of the heterojunction 122, so as to obtain an optimum heterojunction abruptness in accordance with design considerations.

[0074] **FIG. 8B** shows a SEM image of a SGNW structure after gate pattern transfer in accordance with an embodiment of the invention. **FIG. 8B** shows the respective source 112 and drain 116 regions with the SGNW 148 arranged there

between. The gate region **152** overlaps the SGNW **148**. Good alignment of the gate pattern helps to prevent nanowire breakage after gate etching.

**[0075]** FIG. **8C** shows a cross-sectional HRTEM image of a SGNW in accordance with an embodiment of the invention. The SGNW channel **148** is substantially round with a diameter of a range between about 7 nm to about 13 nm. The SGNW **148** has a Ge concentration of about 70%. The SGNW **148** is covered with an HfO<sub>2</sub> dielectric layer **154** on the top and at the sides, and is further supported on the bottom by residual buried SiO<sub>2</sub> **106**, forming an omega-gated channel. Using a fast Fourier transform-based method of HRTEM strain analysis, the SGNW **148** is found to be compressively strained (about -0.6%).

**[0076]** FIG. **9A** shows a SEM image of a SGNW structure after nanowire release in accordance with an embodiment of the invention. During Ge condensation, the SGNW **148** developed a high compressive stress. The released SGNW **148** with Ge concentration of about 85 % were found to be more fragile than Si nanowires of the same dimensions and tend to buckle or break upon oxide removal. Cyclic annealing before oxide removal may be helpful in avoiding breakage due to stress relief or redistribution in the nanowires. In FIG. **9A**, buckled nanowires or buckling on the nanowires **148** can be seen. Ge-rich nanowires can be fragile. The inset shows a plurality of broken nanowires **148**.

**[0077]** FIG. **9B** shows a SEM image of a SGNW structure after nanowire release taken with about 45 degree rotation in accordance with an embodiment of the invention. After implementing stress release temperature cycles, released nanowires remain substantially straight. The substantially straight SGNW **148** is seen bridging the source **112** or drain **116** pads after oxide strip. The inset shows a cross-sectional TEM of the fabricated SGNW **148** with a Ge concentration of about 85 % and a diameter of about 20 nm.

[0078] **FIG. 10A** shows a TEM image of a SGNW GAA FET with  $\text{HfO}_2/\text{TaN}$  gate in accordance with an embodiment of the invention. The  $\text{HfO}_2$  **154** and TaN gate **152** has almost surrounded the SGNW channel **148**. The  $\text{HfO}_2$  **154** is thicker on the top than the sidewalls due to the non-conformal nature of physical vapor deposition (PVD) process. The whitish amorphous layer below the nanowire **148** is  $\text{SiO}_2$  **153** that was not completely removed in the release process

[0079] **FIG. 10B** shows a magnified image of a near-circular SGNW in accordance with an embodiment of the invention. The bright layer at the periphery is a result of Si passivation layer. Similarly, the whitish amorphous layer below the nanowire **148** is a  $\text{SiO}_2$  layer **153** that may not completely removed in the release process. A HRTEM based technique was used to estimate the strain in the nanowires. Using the Si (111) lattice spacing from the substrate as a reference, the SGNW **148** were found to be under lateral compressive strain of about -0.6%.

[0080] **FIG. 10C** shows a reciprocal space diffractogram showing a lattice structure inside the SGNW **148** in accordance with an embodiment of the invention. The calculated strain in the nanowire **148** is about -0.6% compressive. The presence of sharp and distinct spots in the diffractogram implies the absence of defects and good crystallinity in the SGNW **148**.

[0081] The electrical performance of the fabricated heterojunction SGNW p-channel metal-oxide-semiconductor field effect transistor (PMOSFET) is presented in **FIG. 11** and **FIG. 12**. **FIG. 11** shows a normalized  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with gate length ( $L_g$ ) of approximately 350 nm in accordance with an embodiment of the invention. The normalized  $I_D$  vs  $V_D$  characteristics plot of the SGNW PMOSFET are represented by curves **170** and the normalized  $I_D$  vs  $V_D$  characteristics plot of the  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device are represented by curves **172**. The drain current of SGNW **148** may be normalized by its perimeter (assuming a GAA channel with surface inversion) while that of the planar device current may be normalized by channel width. The drive

current of SGNW 148 may be about 4.5 times larger than planar devices. High drive current of SGNW 148 implies large effective mobility for these strained Ge rich nanowire MOSFETs 102 with lateral heterojunction structure.

[0082] FIG. 12 shows a transconductance ( $g_m$ ) vs gate voltage ( $V_G$ ) characteristic plot of a SGNW PMOSFET and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention. The transconductance ( $g_m$ ) vs gate voltage ( $V_G$ ) characteristic plot of the SGNW PMOSFET is represented by curve 174 and the transconductance ( $g_m$ ) vs gate voltage ( $V_G$ ) characteristic plot of the  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device is represented by curve 176. A similar trend to that of the drive current was found for the  $g_m$  value. The peak  $g_m$  value in saturation region as well in linear region for SGNW devices is about 4.5 times larger than for planar devices. Saturation  $g_m$  does not drop too rapidly after the peak, which indicates that on-state channel resistances dominate compared to the parasitic series resistance at lower gate overdrive voltages.

[0083] The enhancement in normalized current and  $g_m$  can mainly be attributed to the following factors. Firstly, owing to the novel hetero-junction structure of SGNW 148, hole velocity is enhanced due to an excess kinetic energy which results from the source to channel valence band offset  $\Delta E_v$ . Secondly, Ge concentration of SGNW channel 148 is 70%, leading to larger hole mobility than the planar channel with lower Ge content. Thirdly, lateral compressive strain (about -0.6%) in the SGNW channel 148 further increases the hole mobility. Fourthly, the nanowire 148 benefits from having a smaller equivalent oxide thickness (EOT) at the sidewalls due to the non-conformal nature of PVD dielectric deposition. However, EOT is thicker at the bottom due to residual buried  $\text{SiO}_2$  oxide 106. Lastly, the SGNW transistor 102 has a smaller access resistance due to the funnel-shaped extension regions.

[0084] For the SGNW 148 with the heterojunction 122 structure, higher hole injection is expected due to the valence band offset from the source region 112 towards the channel region 148. In order to evaluate this aspect, both SGNW 148

and planar devices are characterized at different temperatures and a backscattering coefficient is extracted using a temperature-dependent analytical model:

$$\text{backscattering coefficient } r_{sat} = \frac{1}{1 + \frac{\lambda_0}{l_0}}, \text{ with } \frac{\lambda_0}{l_0} = \frac{4}{0.5 - (\alpha + \frac{\eta}{V_G - V_{T,sat}})} - 2,$$

$$\text{where } \alpha = \frac{\Delta I_{Dsat}}{I_{Dsat} \Delta T}, \text{ and } \eta = \frac{\Delta V_T}{\Delta T}$$

[0085] **FIG. 13** shows a drive current ( $I_{Dsat}$ ) vs temperature characteristic plot of a SGNW PMOSFET and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention. The drive current ( $I_{Dsat}$ ) vs temperature characteristic plot of the SGNW PMOSFET is represented by curve 178 and the drive current ( $I_{Dsat}$ ) vs temperature characteristic plot of the  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device is represented by curve 180. The values  $\alpha$  of SGNW 148 is obtained from the temperature gradient of  $I_{Dsat}$ . As shown in **FIG. 13**,  $\alpha$  of SGNW 148 is about 32% smaller than planar devices. At  $V_G - V_{T,sat} = -2$  V, the calculated values of the backscattering coefficient ' $r_{sat}$ ' for nanowire hetero and planar devices are 0.377 and 0.446 respectively. A reduction of 19% compared to planar devices confirms an increase in ballistic efficiency in these hetero-junction SGNW devices.

[0086] **FIG. 14** shows a threshold voltage ( $V_T$ ) vs temperature characteristics plot of a SGNW PMOSFET 102 and a  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device with  $L_g$  of approximately 350 nm in accordance with an embodiment of the invention. The threshold voltage ( $V_T$ ) vs temperature characteristics plot of a SGNW PMOSFET 102 is represented by curve 179 and the threshold voltage ( $V_T$ ) vs temperature characteristics plot of the  $\text{Si}_{0.7}\text{Ge}_{0.3}$  homo planar device is represented by curve 181. **FIG. 14** shows a constant offset of  $V_T$  vs temperature between the two devices. This may explain the bandgap modification by different Ge content.

[0087] FIG. 15 shows a  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET 102 with  $L_g$  of 500 nm in accordance with an embodiment of the invention. The  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $V_D = -1V$  is represented by curve 182 and the  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $V_D = -0.1V$  is represented by curve 184. The SGNW PMOSFET 102 is formed with an  $HfO_2/TaN$  gate, has a Ge concentration of about 70% and a radius of about 6nm.  $I_D$  is normalized by wire diameter and  $V_T$  is about 0.2V. A subthreshold swing (as obtained from the gradient of the plot) of about 200 mV/dec is obtained. This can possibly be attributed to interface states which could have been caused by Ge diffusion to the gate dielectric interface during thermal processes after Si passivation.

[0088] FIG. 16 shows a  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET 102 with  $L_g$  of 500 nm in accordance with an embodiment of the invention. The  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET 102 with  $L_g$  of 500 nm is represented by curve 185. The SGNW PMOSFET 102 is formed with an  $HfO_2/TaN$  gate, has a Ge concentration of about 70% and a radius of about 6nm. At  $V_G - V_T = -1.2V$ , excellent  $I_D$  performance of about 970  $\mu A/\mu m$  was obtained. This is exceptionally high for p-channel devices of similar gate lengths.

[0089] FIG. 17 shows a  $g_m$  vs  $V_G$  characteristics plot of a SGNW PMOSFET 102 with  $L_g$  of 500 nm in accordance with an embodiment of the invention. The  $g_m$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $V_D = -1V$  is represented by curve 186 and the  $g_m$  vs  $V_G$  characteristics plot of a SGNW PMOSFET with  $V_D = -0.1V$  is represented by curve 188. The SGNW PMOSFET 102 is formed with an  $HfO_2/TaN$  gate, has a Ge concentration of about 70% and a radius of about 6nm and the  $V_T$  is about 0.2. The saturation  $g_m$  peak is located at a large gate overdrive. This implies a lower electric field in the SGNW channel 148 due to the GAA structure.

[0090] FIG. 18 shows a resistance vs  $V_G$  characteristics plot of a SGNW PMOSFET 102 at strong inversion with low  $V_D$  in accordance with an embodiment of the invention. The resistance vs  $V_G$  characteristics plot of a SGNW PMOSFET

**102** at strong inversion with low  $V_D$  is represented by curve **190**. The source or drain series resistance is around  $35k\Omega$  or  $420\ \Omega\text{-}\mu\text{m}$ , which is relatively low.

[0091] A study on the impact of temperature on device parameters is also carried out to find the degradation of SGNW PMOSFET **102** for different gate lengths ( $L_g$ ) or about 350 nm, 400 nm and 500nm respectively. **FIG. 19** shows a  $V_T$  vs temperature characteristics plot of SGNW PMOSFET **102** with respective gate lengths of 350 nm, 400 nm and 500 nm in accordance with an embodiment of the invention. As the temperature increases, threshold voltage shifted positively

[0092] **FIG. 20** shows a linear  $g_m$  peak vs temperature characteristics plot of SGNW PMOSFET **102** with respective gate lengths of 350 nm, 400 nm and 500 nm in accordance with an embodiment of the invention. The linear  $g_m$  peak vs temperature characteristics plot of SGNW with respective gate lengths of 350 nm, 400 nm and 500 nm are represented by curves **192**, **194** and **196** respectively. At temperatures below 340K,  $g_m$  decreases as the temperature increases. When the temperature exceeded 340K, varying the temperature did not have much effect on  $g_m$ . This implies that the degradation of mobility saturated when the temperature exceeded 340K.

[0093] **FIG. 21** shows a  $I_{ON}$  vs  $I_{OFF}$  characteristics plot of SGNW PMOSFET **102** with respective radii of 6 nm and 8 nm in accordance with an embodiment of the invention. The  $I_{ON}$  vs  $I_{OFF}$  characteristics plot of SGNW MOSFET **102** with radii of 6 nm and 8 nm are represented by curves **204** and **206** respectively. SGNWs **148** with smaller nominal radii show enhanced performance. Smaller NW devices (or SGNWs with smaller nominal radii) are likely to have higher Ge content. This causes mobility enhancement due to Ge's intrinsically higher mobility than Si, as well as drastic reduction in alloy scattering effects, which would otherwise degrade mobility in SiGe. This could be responsible for the large enhancement in  $I_{on}$ - $I_{off}$  performance.

[0094] **FIG. 22** shows a  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET **102** with  $\langle 100 \rangle$  channel direction in accordance with an embodiment of the invention. The  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET **102** with  $\langle 100 \rangle$  channel direction and with  $V_D = -1V$  is represented by curve **208** and the  $I_D$  vs  $V_G$  characteristics plot of a SGNW PMOSFET **102** with  $\langle 100 \rangle$  channel direction and with  $V_D = -0.1V$  is represented by curve **210**. The SGNW PMOSFET was formed with a  $HfO_2/TaN$  gate, has a Ge concentration of about 70% and a radius of about 6nm. The gate length  $L_g$  is about 300nm. Plot – is for a  $V_D$  value of -1V and plot – is for a  $V_D$  value of -0.1V.

[0095] **FIG. 23** shows a  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET **102** with  $\langle 100 \rangle$  channel direction in accordance with an embodiment of the invention. The  $I_D$  vs  $V_D$  characteristics plot of a SGNW PMOSFET **102** with  $\langle 100 \rangle$  channel direction is represented by curve **212**. The SGNW PMOSFET **102** is formed with a  $HfO_2/TaN$  gate, has a Ge concentration of about 70% and a radius of about 6nm. The gate length  $L_g$  is about 300nm. This figure shows well behaved transistor characteristics.

[0096] **FIG. 24** shows a  $I_D$  vs  $V_G$  characteristics plot of a unpassivated SGNW n-channel metal-oxide-semiconductor field effect transistor (NMOSFET) in accordance with an embodiment of the invention. The  $I_D$  vs  $V_G$  characteristics plot of a unpassivated SGNW NMOSFET with  $V_D = 1V$  is represented by curve **214** and the  $I_D$  vs  $V_G$  characteristics plot of a unpassivated SGNW NMOSFET with  $V_D = 0.1V$  is represented by curve **216**. Without Si passivation, gate leakage becomes significant despite lower Ge content in SGNW **148**.

[0097] **FIG. 25** shows a  $I_D$  vs  $V_D$  characteristics plot of an unpassivated SGNW NMOSFET in accordance with an embodiment of the invention. The  $I_D$  vs  $V_D$  characteristics plots of an unpassivated SGNW NMOSFET are represented by curve **218**.

[0098] FIG. 26 shows a  $V_{OUT}$  vs  $V_{IN}$  characteristics plot of a CMOS inverter incorporating a SGNW structure in accordance with an embodiment of the invention. The  $V_{OUT}$  vs  $V_{IN}$  characteristics plot of a CMOS inverter incorporating a SGNW structure at different  $V_{DD}$  are represented by curve 220. The inverter characteristics using 30% Ge SGNW NMOSFET and PMOSFET are shown in FIG. 26. The transition is sharp but asymmetric due to high NMOSFET  $V_T$  caused by TaN work function. The inversion can be achieved down to about  $0.2V_{DD}$ , indicating the suitability of low voltage operation of these devices.

[0099] While embodiments of the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

## CLAIMS

What is claimed is:

1. A silicon-germanium nanowire structure arranged on a support substrate, comprising:

at least one germanium-containing supporting portion arranged on the support substrate;

at least one germanium-containing nanowire disposed above the support substrate and arranged adjacent the at least one germanium-containing supporting portion;

wherein germanium concentration of the at least one germanium-containing nanowire is higher than that of the at least one germanium-containing supporting portion, and

wherein a heterojunction is formed at an interface between the at least one germanium-containing nanowire and the at least one germanium-containing supporting portion.

2. The silicon-germanium nanowire structure of claim 1, wherein the ratio of the width of the at least one germanium-containing supporting portion and the diameter of the at least one germanium-containing nanowire is greater than 2.

3. The silicon-germanium nanowire structure of claim 1, further comprising:

an insulating layer arranged between the support substrate and the at least one germanium-containing supporting portion.

4. A transistor comprising the silicon-germanium nanowire structure arranged on a support substrate as defined in any one of claims 1 to 3, the transistor further comprising :

a tunneling layer around the at least one germanium-containing nanowire and

a gate region positioned over the tunneling layer.

5. The transistor of claim 4, further comprising a charge trapping structure surrounding the tunneling layer.
6. The transistor of claim 5, further comprising a blocking layer disposed between the charge trapping structure and the gate region.
7. The transistor of claim 4, wherein the tunneling layer comprises a dielectric material.
8. The transistor of claim 6, wherein the blocking layer comprises a dielectric material.
9. The transistor of claim 7 or 8, wherein the dielectric layer comprises any one or more of a group of dielectric materials of silicon oxide, silicon nitride, magnesium oxide, scandium oxide, hafnium dioxide.
10. The transistor of claim 5, wherein the charge trapping structure comprises any one or more of a group of high dielectric materials of silicon nitride, hafnium dioxide and aluminum oxide.
11. The transistor of claim 4, wherein the at least one germanium-containing supporting portion is doped with either a p-type dopant or an n-type dopant..
12. The transistor of claim 11, wherein the p-type dopant is one or more elements selected from the group consisting of boron, aluminium, gallium and indium.

13. The transistor of claim 11, wherein the n-type dopant is one or more elements selected from the group consisting of phosphorus and arsenic.
14. The transistor of claim 11, wherein the gate region may be doped or undoped.
15. The transistor of claim 14, wherein the gate region is doped with dopants of opposite conductivity to that of the at least one germanium-containing supporting portion.
16. A method of forming a silicon-germanium nanowire structure arranged on a support substrate, the method comprising:
  - forming at least one germanium-containing supporting portion on the support substrate;
  - forming at least one germanium-containing nanowire above the support substrate and adjacent the at least one germanium-containing supporting portion;
  - forming a heterojunction at an interface between the at least one germanium-containing nanowire and the at least one germanium-containing supporting portion;
  - wherein germanium concentration of the at least one germanium-containing nanowire is higher than that of the at least one germanium-containing supporting portion.
17. The method of claim 16, wherein the ratio of the width of the at least one germanium-containing supporting portion and the diameter of the at least one germanium-containing nanowire is greater than 2.
18. The method of claim 16, further comprising:

forming an insulating layer between the support substrate and the at least one germanium-containing supporting portion.

19. The method of claim 16, wherein forming the at least one germanium-containing supporting portion on the support substrate comprises:

depositing a semiconductor device layer on the support substrate;

depositing a starting germanium-containing layer on the semiconductor device layer; and

oxidizing the starting germanium-containing layer and the semiconductor device layer to form a first oxide layer and a resultant germanium-containing layer to form the at least one germanium-containing supporting portion on the support substrate.

20. The method of claim 19, wherein forming the at least one germanium-containing supporting portion on the support substrate further comprises :

removing the first oxide layer by an etching process.

21. The method of claim 19, wherein forming the at least one germanium-containing supporting portion on the support substrate further comprises:

depositing a capping layer on the starting germanium-containing layer.

22. The method of claim 19, wherein oxidizing the starting germanium-containing layer and the semiconductor device layer is performed by a germanium condensation process.

23. The method of claim 16, wherein forming the at least one germanium-containing nanowire above the support substrate and adjacent the at least one germanium-containing supporting portion comprises:

depositing a semiconductor device layer on the support substrate;

depositing a starting germanium-containing layer on the semiconductor device layer;

oxidizing the starting germanium-containing layer and the semiconductor device layer to form a first oxide layer and a resultant germanium-containing layer;

patterning the resultant germanium-containing layer to form a fin structure, the fin structure comprising the at least one germanium-containing supporting portion arranged on the support substrate and the at least one germanium-containing nanowire disposed above the support substrate and arranged adjacent the at least one germanium-containing supporting portion; and

further oxidizing at least the fin portion to form the at least one germanium-containing nanowire surrounded by a second oxide layer.

24. The method of claim 23, wherein forming at least one germanium-containing nanowire above the support substrate and adjacent the at least one germanium-containing supporting portion further comprises:

removing the first oxide layer and the second oxide layer by an etching process.

25. The method of claim 23, wherein forming at least one germanium-containing nanowire above the support substrate and adjacent the at least one germanium-containing supporting portion further comprises:

depositing a capping layer on the starting germanium-containing layer.

26. The method of claim 23, wherein oxidizing at least the fin portion is performed by a germanium condensation process.
27. The method of claim 19 or claim 23, wherein the semiconductor device layer comprises a silicon layer.
28. The method of claim 19 or claim 23, wherein the starting germanium-containing layer comprises a silicon-germanium layer.
29. The method of claim 19 or claim 23, wherein the resultant germanium-containing layer comprises a silicon-germanium layer.
30. The method of claim 19 or claim 23, wherein the first oxide layer comprises a silicon-oxide layer.
31. The method of claim 23, wherein the second oxide layer comprises a silicon-oxide layer.
32. The method of forming a transistor comprising forming the silicon-germanium nanowire structure arranged on a support substrate as defined in any one of claims 16 to 31, the method further comprising:  
  
forming a tunneling layer around the at least one germanium-containing nanowire and  
  
forming a gate region positioned over the tunneling layer.

33. The method of claim 33, further comprising forming a charge trapping structure surrounding the tunneling layer.
34. The method of claim 33, further comprising forming a blocking layer disposed between the charge trapping structure and the gate region.
35. The method of claim 32, wherein the tunneling layer comprises a dielectric material.
36. The method of claim 34, wherein the blocking layer comprises a dielectric material.
37. The method of claim 35 or 36, wherein the dielectric layer comprises any one or more of a group of dielectric materials of silicon oxide, silicon nitride, magnesium oxide, scandium oxide, hafnium dioxide.
38. The method of claim 33, wherein the charge trapping structure comprises any one or more of a group of high dielectric materials of silicon nitride, hafnium dioxide and aluminum oxide.
39. The method of claim 16, further comprising:
- doping the at least one germanium-containing supporting portion with either a p-type dopant or an n-type dopant.
40. The method of claim 39, wherein the p-type dopant is one or more elements selected from the group consisting of boron, aluminium, gallium and indium.
41. The method of claim 39, wherein the n-type dopant is one or more elements selected from the group consisting of phosphorus and arsenic.

42. The method of claim 39, further comprising:

doping the gate region with a dopant of opposite conductivity to that of the at least one germanium-containing supporting portion.