Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp571-572

3D-stacked Highly Strained SiGe/Ge Gate-All-Around (GAA) pFETs Fabricated by 3D Ge Condensation

Junkyo Suh[1*], Andrew C. Meng[2], Taeho R. Kim[2], Ann F. Marshall[2], Anahita Pakzad[3], Paul C. McIntyre[2] and Krishna C. Saraswat[1,2]

[1]Department of Electrical Engineering Dept., Stanford University, Stanford, CA 94305, USA., [*]E-mail: suhjk@stanford.edu

[2]Department of Material Science & Engineering Dept., Stanford University, Stanford, CA 94305, USA.

[3]Gatan Inc., Pleasanton, CA 9588, USA.

Abstract: This paper reports on 3D stacking of highly strained SiGe/Ge GAA pFETs fabricated by 3D Ge condensation. Our proposed method is highly stackable with either nanosheet (NS) or nanowire (NW) channels and does not require strain relaxed buffers (SRB) to incorporate strain in channels. 3D Ge condensation of suspended channels enables achieving uniaxial compressive strain of ~2.5%, confirmed by diffraction pattern using scanning transmission electron microscopy (STEM). Through the geometric optimization of channels, compressive strain can be effectively increased with less buckling, resulting in the suppression of undesirable hole generation. As a result, high hole mobility (μ) of 617 cm^2/Vs is demonstrated.

Introduction: Incorporating high mobility material in channel and 3D stacking channels in a multigate/surroundgate device can enable next-generation high-performance CMOS technology [1,2]. Ge is a potential channel material due to its superior μ and light effective mass. Also, Ge condensation is an appealing technique to introduce strained Ge (s-Ge) onto Si platform without SRB as a result of its excellent compatibility with Si technology and, more importantly, the ease of controlling critical dimension (CD) [3]. However, the conventional Ge condensation on SOI does not allow 3D stacking of channels and shows a large degree of strain relaxation [3,4]. We propose a novel method with high stackability to fabricate 3D-stacked strained SiGe/Ge GAA device architecture with large uniaxial compressive strain by 3D Ge condensation.

3D stacking of strained SiGe/Ge by 3D Ge condensation

Fig. 1a displays the schematic of our 3D-stacked Ge GAA structure and Fig. 1b shows a scanning electron microscopy (SEM) image of the structure. High quality pseudomorphic SiGe multilayers are grown on Si and patterned. The SiGe channels are released by tetramethylammonium hydroxide (TMAH), followed by Ge condensation [3] all around the channels (3D) to achieve Ge-rich SiGe or pure Ge. It should be pointed out that the suspended $Si_{0.7}Ge_{0.3}$ becomes Ge-rich SiGe as Ge condensation proceeds while S/D remain Si-rich SiGe, which allows our structure to be highly compatible with the incumbent Si contact technology, especially for nFETs. It is confirmed by X-ray diffraction (XRD) that the peak of the initial $Si_{0.7}Ge_{0.3}$ is split into two in which one approaches Ge peak and the other one (S/D) moves towards Si peak (Fig. 3). Raman spectra are taken over the course of 3D Ge condensation (Fig. 4) to determine Ge composition and strain [5]. Fig. 5 shows Raman spectral imagining of Ge-Ge mode along with the SEM image of 3D-stacked GAA, which supports the idea that Ge enrichment takes place only in the channel, consistent with Fig. 3. NS and NW configurations (Fig. 6) can be made by proper sizing of initial SiGe and fin width before the channel release. High quality of single crystalline Ge NW is captured by TEM (Fig. 7).

4D-STEM strain mapping of stacked NWs

Buckling of long NWs (high aspect ratio (AR)) caused by Ge condensation induced compression is observed in Fig. 8. To further understand this, 4D-STEM strain mapping is used to measure strain distribution in 200nm and 500nm long $Si_{0.25}Ge_{0.75}$ NWs. To ensure accuracy, line scans from the Si bulk through the centers of each NW are performed: NW diffraction patterns are compared to those of the Si bulk. Fig. 9a reveals the uniaxial compressive strain for the 500nm long NWs along its length to be ~1.2% (line scan along the NW length is also shown). In contrast, Fig. 9b shows compressive strain for the 200nm long NWs along their length to be ~2.5%. Accommodation of the higher compressive strain in the shorter NWs (small AR) is supported by the observation of increased buckling in longer NWs (Fig. 8), consistent with strain relaxation being limited by the smaller AR of the NWs. Therefore, through the geometric optimization of GAA channels, it is possible to achieve high compressive strain, which benefits the performance of pFETs [1,3,4].

Highly strained SiGe/Ge GAA pFETs

To examine the electrical characteristics, 3-stacked s-SiGe GAA pFETs are fabricated with 10nm Al_2O_3/25nm TiN gate stack [6] and metal S/D. Fig. 10a shows I_D-V_{GS} characteristics with 60% and 75% Ge. It should be pointed out that V_{th} does not shift positively with higher Ge %, indicative of high quality channels produced by our method without a significant amount of undesirable hole generation by crystal defects [4]. I_D-V_{DS} is shown in Fig. 10b, demonstrating that 3D stacking enables the high drivability of the pFETs in a limited footprint. Fig. 11a shows V_{ext} shift (V_{ext}: Intercept at V_{GS} axis of linear extrapolation of I_D-V_{GS} at g_m max.) with respect to V_{ext} at NW length (L_{NW})=200nm as a function of L_{NW}. It should be highlighted that more positive V_{ext} shifts are observed at the longer NWs (high AR), attributable to defect induced hole generation through buckling, consistent with Fig. 8. High hole mobility of 617 cm^2/Vs (Fig. 11b), extracted by Y-function, is achieved, ascribed to high Ge % combined with high uniaxial compressive strain in the channels.

Conclusions: We have demonstrated a novel method of fabricating 3D-stacked strained SiGe/Ge GAA by 3D Ge condensation. The method allows Ge-rich SiGe and/or Ge to be incorporated in channel with a large uniaxial compressive strain. NS and NW GAA device architecture can be fabricated. Through the geometric optimization of GAA channels, the large uniaxial compressive strain of ~2.5% and the excellent electrical characteristics of the pFETs with high hole mobility of 617 cm^2/Vs are demonstrated.

Reference: [1] N. Loubet et al., VLSI (2017) [2] H. Mertens et al., IEDM (2017) [3] J. Suh et al., SSE (2016) [4] J. Suh et al., DRC (2009) [5] F. Pezzoli et al., Mat. Sci. Semicond .Proc., 11 (2008) [6] S. Swaminathan et al., APL 95, 2009 [7] T.C. Pekin et al., Ultramicroscopy, 176 (2016)

Acknowledgement: This work was supported in part by the Stanford SystemX Alliance, by the U.S. Naval Research Lab., by SNF and SNSF.

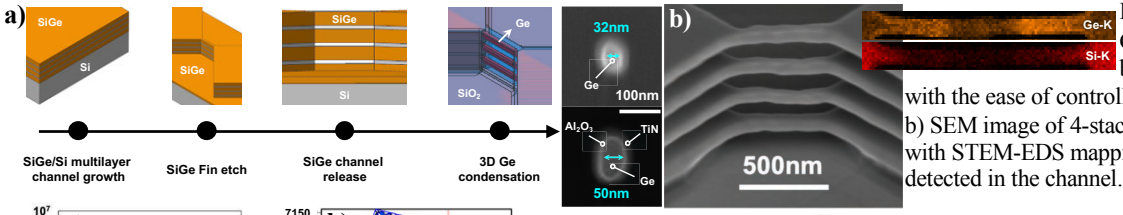
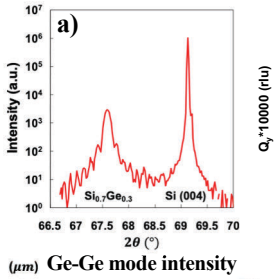


Fig. 1: a) 3D-stacked Ge GAA structure fabricated by 3D Ge condensation with the ease of controlling CD of NW diameter. b) SEM image of 4-stacked suspended Ge NWs with STEM-EDS mapping of Ge and Si. Si is not detected in the channel.



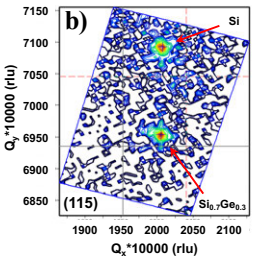


Fig. 2: a) High quality pseudomorphic $Si_{0.7}Ge_{0.3}$ is grown on Si bulk, confirmed by XRD 2θ-ω scan. b) XRD reciprocal space mapping (RSM) reveals that fully strained $Si_{0.7}Ge_{0.3}$ is grown on Si.

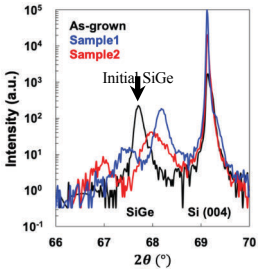


Fig. 3: Black, **blue** and **red** solid curves correspond to **as-grown** and samples with **short** and **long** time Ge condensation, respectively. XRD 2θ-ω scans show that the single peak of the initial SiGe is split into two peaks in which one (channel) approaches Ge peak and the other one (S/D) moves towards Si peak.

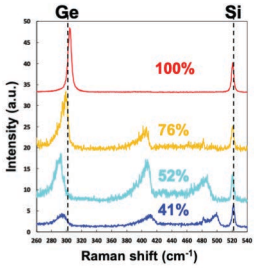


Fig. 4: Raman spectra are taken during 3D Ge condensation to determine Ge composition and strain [4]. Numbers in the figure are Ge contents over the course of Ge condensation.

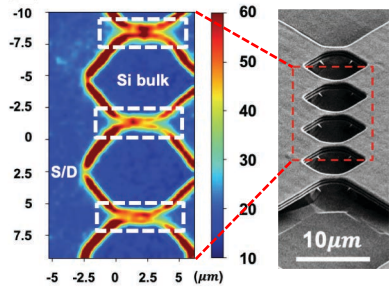


Fig. 5: Raman spectral imaging along with the corresponding SEM image. Ge enrichment takes place in the channel (white dotted box) whereas S/D remain Si-rich SiGe owing to Si sandwiched by SiGe.

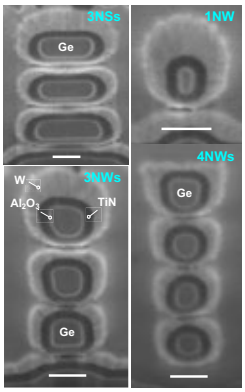


Fig. 6: Cross-sectional SEM images of Ge NS and NW channels by properly sizing initial expitaxial SiGe thickness and fin width before the SiGe channel release. All scale bars are 100nm.

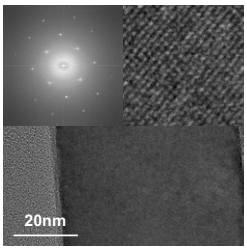


Fig. 7: High resolution TEM (HRTEM) of single crystalline Ge NW with Fast Fourier Transform (FFT) and lattice images.

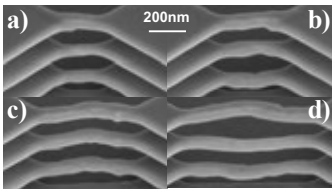


Fig. 8: Suspended NWs with L_{NW} of a) 200nm, b) 300nm, c) 500nm and d) 700nm (different ARs). More buckling (strain relaxation) caused by Ge condensation induced compression is observed in the longer NWs. Geometric optimization of NW is required to maximize strain.

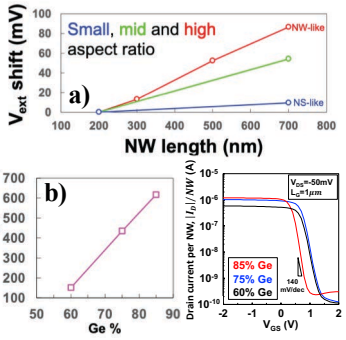


Fig. 11: a) V_{ext} vs. L_{NW}. Positivie V_{ext} shifts in the longer NWs due to defect induced holes through buckling. b) High hole mobility of 617 cm^2/Vs is achieved owing to high Ge % and large compressive strain. I_D-V_{GS} with various Ge % is also shown.

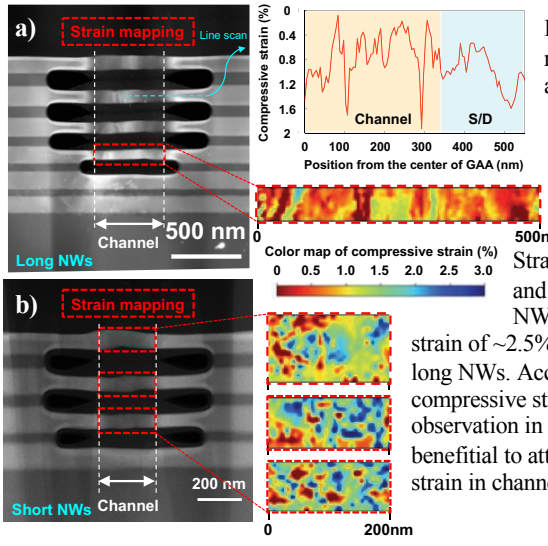


Fig. 9: 4D-STEM strain distribution analysis by nanobeam diffraction (NBD). 4D-STEM is advantageous for measuring strain in released NWs that bend to relax strains due to lower sensitivity to sample tilt than geometric phase analysis (GPA) [7]. Strain mapping of a) 500nm and b) 200nm long 75% Ge NWs. Uniaxial compressive strain of ~2.5% is achieved in the 200nm long NWs. Accomodation of the higher compressive strain is supported by the observation in Fig. 8. Small AR is benefitial to attain high compressive strain in channels.

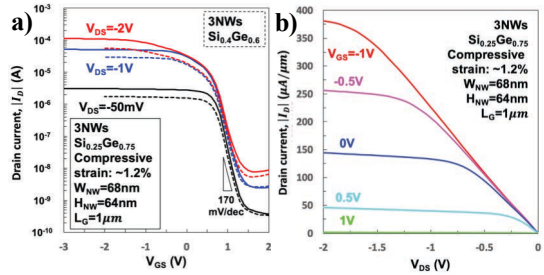


Fig. 10: a) I_D-V_G characteristics of the 3-stacked s-SiGe GAA pFETs. V_{th} does not shift positively with higher Ge %, indicative of high quality channels. b) I_D-V_{DS} characteristics. The drain current is normalized by the perimeter of NWs.