Performance Improvement in Uniaxially Tensile Stressed GeSn FinTFET Investigated by Simulation: Impact of Stress Direction

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Abstract
We demonstrate the performance improvement in fin tunnel field effect transistors (FinTFETs) using uniaxial tensile stress by simulation. The fin rotates within the (001) plane and the uniaxial tensile stress is always along the fin direction. Under the same magnitude of stress, line-FinTFETs achieve the more pronounced \( G_{TBT} \) and \( I_{ON} \) enhancement over the point-FinTFETs. Simulation results show that the improvement effect of tensile stress on GeSn FinTFETs shows strong dependence on stress direction.

1. Introduction
Tunneling FET (TFET) is considered as a promising candidate for ultralow power consumption applications [1]-[4]. One key challenge that TFET still faces is, how to obtain sufficient on-state current (\( I_{ON} \)). GeSn, which can be easily integrated on Si, has attracted tremendous research interests for TFET fabrication thanks to the indirect-to-direct transition and bandgap \( E_G \) reduction with Sn incorporation thus boosting the band-to-band tunnel (BTBT) efficiency [5]-[9]. However, Sn composition cannot increases arbitrary due to the limitation of solid solubility for Sn in Ge. Strain engineering is another effective way to further enhance the performance of GeSn based TFET [10], [11].

In this work, uniaxially tensile stressed GeSn line- and point-FinTFETs on (001) plane are characterized by numerical simulation. As a uniaxial tensile stress is applied along the fin direction, the \( G_{TBT} \) and \( I_{ON} \) enhancement of GeSn FinTFETs is demonstrated. The stress direction and tunneling mode dependent performance improvement of the devices are discussed.

2. Band Structures of Uniaxially Tensile Stressed GeSn
The comparison of \( E-k \) bands near \( \Gamma \)-point for relaxed and uniaxially tensile stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \) calculated by \( k \)-p method is shown in Fig. 1. The stress with the magnitude of 1GPa is along [110] direction. Tensile-stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \) demonstrates a significant decreasing in conduction band edge energy and a lifting degeneracy of valence bands over the relaxed case, which contributes to the smaller \( E_G \). The higher and lower valence bands are denoted by V1 and V2, respectively. Under stress, the effective masses of V1 and V2 exhibit different variations along the directions parallel and perpendicular to the uniaxial stress.

Fig. 2 shows the direct \( E_G \) of relaxed and 1GPa uniaxially tensile-stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \) and the stress directions rotate in the (001) plane. In this work, the corresponding directions always shows the stress (i.e. fin) directions, and 0° and 90° are [100] and [010], respectively. \( E_G \) between conduction valley to V1 and V2 in stressed materials, denoted by \( E_{GL-V1} \) and \( E_{GL-V2} \), respectively, are smaller that than of relaxed material.

Besides the \( E_G \), the BTBT rate in GeSn is also directly related to the reduced tunneling mass \( m_r \). In the BTBT process, the light hole band is the only valence band that couples to the \( \Gamma \) conduction band, and \( m_r \) is calculated by \( m_r = (m_e \times m_h)/(m_e + m_h) \), where \( m_e \) and \( m_h \) are the effective masses of electron and light hole, respectively. As the uniaxial stress rotates within the (001) plane, \( m_r \) in the plane along and perpendicular to the stress directions was calculated based on the electron and light hole effective masses extracted from the band diagram by utilizing the energy dispersions near the \( \Gamma \) point (Fig. 3). It is observed that \( m_r \) of stressed GeSn along stress direction is larger than that of relaxed material which is against the boosting of tunneling probability. While for stressed GeSn that perpendicular to the stress direction,

Fig. 1. E-k energy band diagrams of relaxed and 1GPa uniaxially tensile stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \) where the stress is along [110] direction.

Fig. 2. Direct \( E_G \) for relaxed and 1GPa uniaxially tensile stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \). Stress directions rotate in the (001) plane.

Fig. 3. Values of \( m_r \) for relaxed and 1GPa uniaxially tensile stressed \( \text{Ge}_{0.90}\text{Sn}_{0.10} \) along stress direction and perpendicular to the direction of stress.

3. Device Design and Simulation Methodology
To investigate the impact of stress on the BTBT along stress direction as well as that perpendicular to the stress direction, GeSn point- and line-FinTFETs are designed and shown in Fig. 4(a) and (b), respectively. The structure parameters are also shown. The devices are on (001) plane, and as fin rotates in plane, stress is always along the fin direction. Self-consistent device simulations were carried out utilizing TCAD simulator, which implements a dynamic nonlocal tunneling algorithm. BTBT was calculated based on Kane’s model [12]. Quantum confinement model provided by software was taken into account.
Fig. 4. 3D Schematics of Ge<sub>0.90</sub>Sn<sub>0.10</sub> (a) point-FinTFET and (b) line-FinTFET.

![Diagram](image_url)

Fig. 5. Enhancement of G<sub>ON</sub> for 1GPa uniaxially tensile stressed Ge<sub>0.90</sub>Sn<sub>0.10</sub> along stress direction and perpendicular to the direction of stress over the relaxed material.

4. Electrical Results

Fig. 5 shows the enhancement of BTBT generation rate G<sub>BTBT</sub> at a fixed electric filed F of 2 MV/cm for Ge<sub>0.90</sub>Sn<sub>0.10</sub> under 1GPa uniaxial tensile stress over the relaxed material. As fin rotates, BTBT along the directions perpendicular to the stress achieves the significant G<sub>BTBT</sub> improvement in comparison with the relaxed cases as well as those along the stress directions, owing to the smaller E<sub>G</sub> and m<sub>e</sub>. G<sub>BTBT</sub> along stress direction and perpendicular to the stress direction correspond to the point- and line-FinTFETs, respectively (as shown in Fig. 6). So, line-FinTFETs are expected to obtain the improved tunneling current under the uniaxial tensile stress.

Fig. 6(a) and (b) illustrate the counter plots of carrier G<sub>BTBT</sub> distributions for relaxed Ge<sub>0.90</sub>Sn<sub>0.10</sub> line- and point-FinTFETs in on state, respectively. It exhibits that the BTBT perpendicular to the direction of channel dominates the drive current in line-FinTFET, while, the drive current of point-FinTFET is dominated by the BTBT along channel direction.

(a) Line-FinTFET @ V<sub>DS</sub>=0.725V, V<sub>GS</sub>=0.3V  (b) Point-FinTFET @ V<sub>DS</sub>=1V, V<sub>GS</sub>=0.3V

![Diagram](image_url)

The simulated I<sub>DS</sub>-V<sub>DS</sub> curves of the relaxed and 1GPa uniaxially tensile stressed Ge<sub>0.90</sub>Sn<sub>0.10</sub> point- and line-FinTFETs at a V<sub>DS</sub> of 0.3 V were extracted and shown in Fig. 7. The improvement effect of tensile strain on I<sub>DS</sub> of GeSn line-FinTFETs is more remarkable compared to the point-transistors.

Fig. 7. Simulated I<sub>DS</sub>-V<sub>GS</sub> curves for relaxed and 1GPa uniaxially tensile stressed Ge<sub>0.90</sub>Sn<sub>0.10</sub> (a) point-FinTFET (b) line-FinTFET.

![Diagram](image_url)

5. Conclusions

Uniaxially tensile stressed Ge<sub>0.90</sub>Sn<sub>0.10</sub> FinTFETs on (001) plane are investigated via numerical simulation. The fin rotates within (001) plane and the stress is applied along fin direction. The boosting effect of uniaxial tensile stress on the device performance strongly depends on stress direction. Under 1 GPa tensile stress, line-FinTFET with [110] fin direction achieve a 99.3% I<sub>ON</sub> improvement over the relaxed devices at V<sub>DS</sub> of 0.3 V.

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References