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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_{BTBT} 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, uniaxial 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_{BTBT} 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 Γ-point for relaxed and uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$, calculated by k·p method is shown in Fig. 1. The stress with the magnitude of 1GPa is along [110] direction. Tensile-stressed $Ge_{0.90}Sn_{0.10}$ 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 direct 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 $Ge_{0.90}Sn_{0.10}$, 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 $E_{G,\Gamma\text{-V1}}$ and $E_{G,\Gamma\text{-V2}}$, respectively, are smaller than that 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 Γ conduction band, and m_r is calculated by $m_r = (m_e \times m_{lh})/(m_e + m_{lh})$, where m_e and m_{lh} 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 Γ 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,

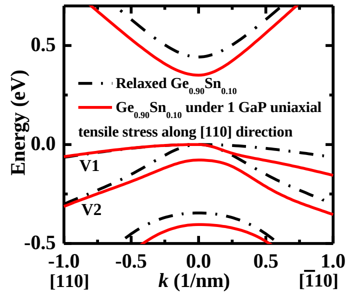

Fig. 1. *E-k* energy band diagrams of relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ where the stress is along [110] direction.

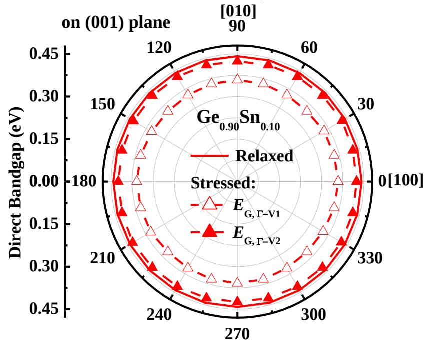

Fig. 2. Direct E_G for relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$. Stress directions rotate in the (001) plane.

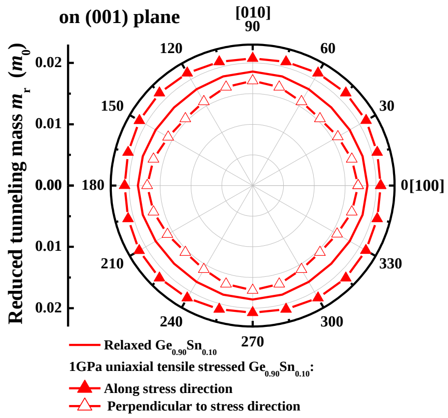

Fig. 3. Values of m_r for relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ along stress direction and perpendicular to the direction of stress.

m_r is smaller than that of relaxed material contributing to the enhancement of BTBT rate. We also observed that the impact of stress on m_r exhibits the strong direction dependence.

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.

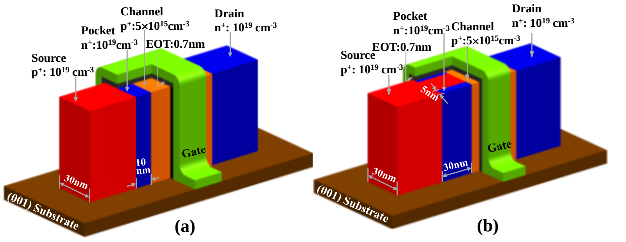

Fig. 4. 3D Schematics of $Ge_{0.90}Sn_{0.10}$ (a) point-FinTFET and (b) line-FinTFET.

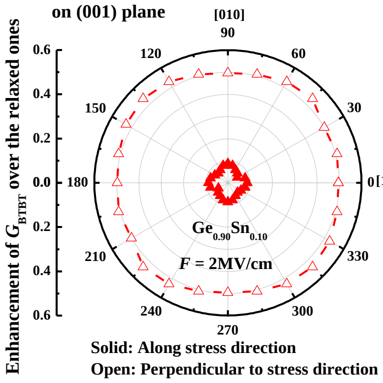

Fig. 5. Enhancement of G_{BTBT} for 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ along stress direction and perpendicular to the direction of stress over the relaxed material.

4. Electrical Results

Fig. 5 shows the enhancement of BTBT generation rate G_{BTBT} at a fixed electric filed F of 2 MV/cm for $Ge_{0.90}Sn_{0.10}$ under 1GPa uniaxial tensile stress over the relaxed material. As fin rotates, BTBT along the directions perpendicular to the stress achieves the significant G_{BTBT} improvement in comparison with the relaxed cases as well as those along the stress directions, owing to the smaller E_G and m_r. G_{BTBT} 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_{BTBT} distributions for relaxed $Ge_{0.90}Sn_{0.10}$ 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.

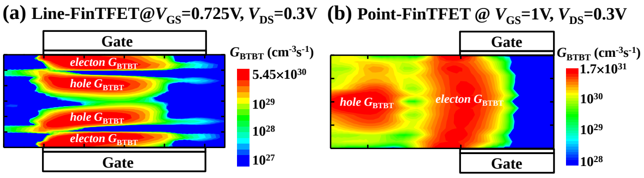

Fig. 6. Counter plots for carrier generation rate G_{BTBT} of relaxed $Ge_{0.90}Sn_{0.10}$ (a) line- and (b) point-FinTFETs in on state indicating that the BTBT perpendicular to the channel direction and along channel direction dominates the tunneling current in line- and point-FinTFETs, respectively.

The simulated I_{DS}-V_{GS} curves of the relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ point- and line-FinTFETs at a V_{DS} of 0.3 V were extracted and shown in Fig. 7. The improvement effect of tensile stress on I_{DS} of GeSn line-FinTFETs is more remarkable compared to the point-transistors.

Fig. 8 summaries the I_{ON} of relaxed and uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ line- and point-FinTFETs with fin rotating in (001) plane at fixed V_{GS}-V_{TH}=V_{DS}=0.3V. V_{TH} is defined as V_{GS} at I_{DS} of 10^{-10} A/μm, and for the stressed line-FinTFET, V_{TH} is the

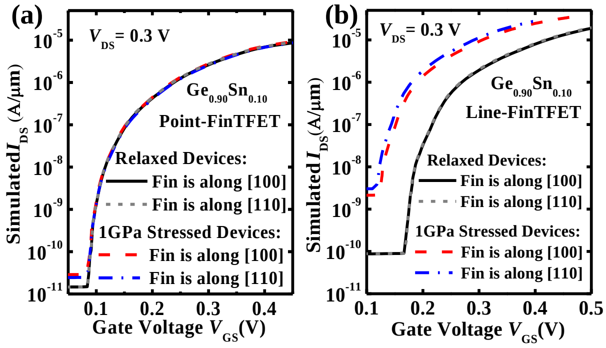

Fig. 7. Simulated I_{DS}-V_{GS} curves for relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ (a) point-FinTFET (b) line-FinTFET.

turn-on voltage of BTBT. Under the same tensile stress, Line-FinTFETs exhibit larger I_{ON} enhancement over point device attributing to the smaller E_G and m_r. Under 1GPa uniaxial tensile stress, $Ge_{0.90}Sn_{0.10}$ point-FinTFET along [100] directions achieve 7.6% I_{ON} enhancement, while for line-FinTFET along [110] direction achieve 99.3% I_{ON} enhancement over the relaxed devices at V_{DD} of 0.3 V. The enhancement of I_{ON} varies with the stress directions indicating that the impacts of uniaxial tensile stress on $Ge_{0.90}Sn_{0.10}$ TFETs have strong dependence on stress direction.

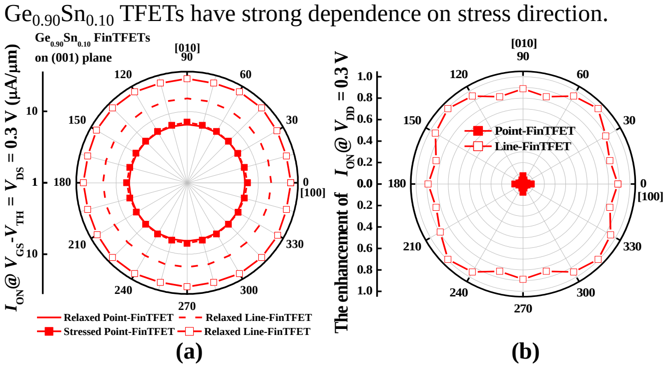

Fig. 8. (a) Comparison of I_{ON} for relaxed and 1GPa uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ point- and line-FinTFETs at V_{GS}-V_{TH}=V_{DS}=0.3 V. (b) Enhancement of I_{ON} for uniaxially stressed GeSn point- and line-FinTFETs over relaxed devices along various directions at V_{DD} of 0.3 V.

5. Conclusions

Uniaxially tensile stressed $Ge_{0.90}Sn_{0.10}$ 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_{ON} improvement over the relaxed devices at V_{DD} of 0.3 V.

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