Investigation of the performance of Strained Ballistic Nanowire Tunnel FET

Anup Dey

Electronics and Communication Engineering Department, Jalpaiguri Government Engineering College, Jalpaiguri, India

a_dey2002@yahoo.com

Abstract: We have investigated the physics of ballistic nanowire tunneling Field Eeffect Transistor (TFET) under arbitary stress to provide an accurate physical picture. TheI-V characteristic of the strained TFET (sTFET) is shown and the mechanism of the device operation was discussed. The anisotropic band structure of bulk state under strain is first computed and then applied to two-dimensional cofinement in nanowire. The strain alters the carrires statistics in the in-plane and perpendicular directions besides changing the effective mass tensors. This eventually increases the interband transition probability causing higher ON-state current relative to the unstrained materials. Different possible methodologies to reduce OFF-current are also indicated. Finally, our physical models were verified against the previously reported experimental results.

Keywords: Tunnel FET; strain; VLSI; device technology.

1 INTRODUCTION

The TFET (tunneling-FET) emerges as promising device to replace the traditional MOSFET especially for low standby power (LSTP) applications [1] .However, the greatest challenge for silicon tunnel FETs [1] is possibly the improvement of on current I_{on} while retaining low off current I_{off} thereby keeping lowered inverse subthreshold slope (SS). To meet these objectives many possible alternatives are tried and investigated which includes the use of high-κ dielectrics, spacers, and underlaps [2, 3] graphane based TFETs and]; strain in Si, Ge, and SiGe tunnel FETs [4].

Upon application of appropriate strain the carrires statistics in the in-plane and perpendicular directions can be altered besides modifying the energy dispersion and hence the effective mass tensors. This eventually results in increased interband transition probability causing higher ON-state current relative to the unstrained materials. Although a significant number of experimental and simulations results are available in the literature the underlying physics to improve device performance by strain engineering is relatively poor. In this paper we systematically develop a ballistic current model to analyze the performance of a strained nanowire Si-TFET (sTFET).

2 DEVICE MODELING WITH STRAIN

2.1 ON State Current Model

To begin with we shall demonstrate our modeling with a p-TFET. The p-FET and n-FET device structures are identical. In both p-FET and n-FET operation, the n+ regions are set at a higher voltage than that of p+ and the source and drain terminal definitions in the p-FET is just get reversed in case

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of n-FET. The energy band profile along the channel (assumed in the *z*-direction) for a BTBT (band-to-band-tunneling) p-FET is shown in Fig. 1. Fig. 1 the E_{FD} and the E_{FS} are the drain and source electrochemical potentials, respectively, with $E_{FD} > E_{FS}$ (applied voltage is positive at the n+ source) .Without gate bias the carrier flow is prevented due to the energy barrier created by the bandgap $E_g{}'$ of the strained channel material. When appropriate negative gate bias is applied, the top of the valence band inside the channel ($E_{V,\text{channel}}$) goes above the bottom of the conduction band within n+ source region ($E_{C,\text{source}}$), an energy pass window is created. Significant amount of tunneling current can flow across the reverse biased source n+-i junction if sufficient longitudinal electric field is provided by the applied bias. In order to model the drain current flowing through the BTBT device, we assume ballistic mode of carrier transport. Investigation of the longitudinal energy band profile both in the ON and OFF states of the device is essential for modeling interband tunneling current. The ON-state energy band profile in the longitudinal *z*-direction has been shown in Fig. 2. E_{FS} and E_{FD} are defined, respectively, as the source and drain electrochemical potentials [5]. For simplicity, p+ drain doping concentration is chosen such that the top of the valence band on p^+ is just aligned with E_{FD}, whereas the bottom of the conduction band on the source n+ region ($E_{C,\text{source}}$) is aligned below E_{FS} by an energy offset of E_d(being= $E_{FS} - E_{C,\text{source}}$). Positive value of E_d signifies the source degeneracy and thus how heavily the source is doped. While a negative value of *E*d ($|E_\text{d}| > 3\ kT$) ensures source nondegeneracy. With negative gate bias the created energy pass band between the top of the intrinsic valence band ($E_{V,\text{channel}}$) and $E_{C,\text{source}}$ is defined as $\Delta\Phi(= E_{V,\text{channel}} - E_{C,\text{source}})$ and as is shown in Fig. 2. The ΔΦ increases only with the applied negative gate voltage in a BTBT p-FET operating in superthreshold, and ΔΦ does not get modulated enough by the drain potential due to negligible drain-induced barrier lowering in this context. In our case, the threshold voltage (V_th) of a BTBT p-FET is defined as that particular gate-to-source potential (V_{GS}) when $E_{V,\text{channel}}$ gets perfectly aligned $E_{C,\text{source}}$ (or in otherwords $\Delta\ \Phi = 0$ eV). For a negative ΔΦ, the device is said to operate in subthresold. The threshold voltage (V_th) then can be defined as

$$V_{th} = V_{ox} + \frac{E_g{}'}{2q} - \frac{E_d}{q} \tag{1}$$

where $E_g{}'$ is the strained band gap of the channel material and V_{ox} is the voltage drop across the channel. Assuming ballistic transport the BTBT current in the ON state can be calculated using the Landauer's formula as

$$I_{on} = \frac{2q}{\text{h}} \int_{E_{C,\text{source}}}^{E_{V,\text{channel}}} T_{BTBT}(E) D_1(E) [f_S(E) - f_D(E)] v_z(E) dE \tag{2}$$

where $T_{BTBT}(E)$ is the BTBT transmission probability, $D_1(E)$ is the one dimentional (1-D) density of states of the strained nanowire material, $v_z(E)$ is the strained carrier velocity resolved in the x-direction, q and h are, respectively, the electronic charge, and Planck's constant and $f_S(E)$ and $f_D(E)$ are, respectively, the source–drain Fermi distribution functions expressed as [5]

$$f_{S/D}(E) = \frac{1}{1 + \exp\left(\frac{E - E_{FS/FD}}{kT}\right)} \tag{3}$$

k being the Boltzmann constant. The 1-D density of states $D_1(E)$ of the strained nanowire and carrier velocity along z-direction $v_z(E)$ are the band structure dependent parameters and hence significantly changes with the strain relative to the material when relaxed. Here $T_{BTBT}(E)$ is constant at a particular gate and source bias, and can be taken out of the integral. Performing the integration over the energy pass window the BTBT ON current expression gets simplified as

$$I_{on} = \frac{2q}{\text{h}} T_{BTBT}(E) \ln\left[\frac{\left(1 + \exp\left(\frac{E_{C,\text{source}} - E_{FS} + \Delta\Phi}{kT}\right)\right)\left(1 + \exp\left(\frac{E_{C,\text{source}} - E_{FD}}{kT}\right)\right)}{\left(1 + \exp\left(\frac{E_{C,\text{source}} - E_{FD} + \Delta\Phi}{kT}\right)\right)\left(1 + \exp\left(\frac{E_{C,\text{source}} - E_{FS}}{kT}\right)\right)}\right] \tag{4}$$

Now in order to express the I_{on} in terms of the intrinsic parameters of the TFET and the applied bias, the transmission probability of triangular potential barrier for the quantum wire as shown in Fig. 2, using the WKB approximation, can be written in the following form

$$T_{BTBT}(E) \cong \exp(-\alpha \frac{\lambda_s}{E_g{}' + \Delta\Phi}) \tag{5}$$

where $\alpha = 4\left(E_g{}'\right)^{3/2} \sqrt{2m_r} / 3q\text{h}$ and the screening length λ_s for quantum wire can be written as[17]

$$\lambda_s = \sqrt{(\varepsilon_{ch} / 8\varepsilon_{ox}) d_{ch}^2 \ln\left[\left(1 + 2\frac{t_{ox}}{d_{ch}}\right) + \varepsilon_{ox} d_{ch}^2\right]} \tag{6}$$

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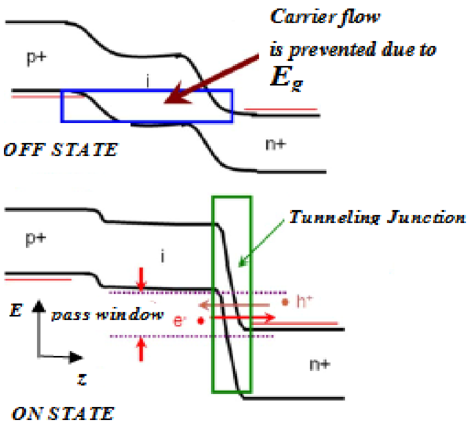

Fig. 1. Energy band diagram of a btbt nanowire p-fet.

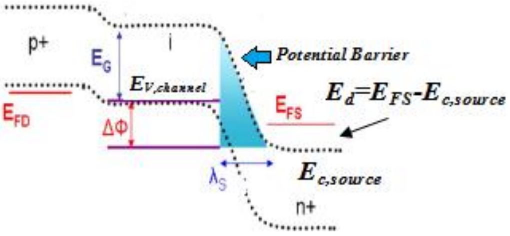

Fig. 2. Triangular potential barrier and carrier tunneling in the on sate.

2.2 Strained Bandstructure

Following Bir and Pikus 4×4 Hamiltonian [6], under the **k·p** framework, the valence band dispersion under Biaxial Stress for small k limit can be written as

$$E_v(k) = -P_\varepsilon - Q_\varepsilon \text{ m}\frac{\text{h}^2}{2m_0}[(\gamma_1+\gamma_2)k_t^2+(\gamma_1+\gamma_2)k_z^2] \tag{7}$$

where γ_i are Luttinger parameters, and k_t the in-plane wave vector and

$$P_\varepsilon = a_v(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}) \tag{8}$$

$$Q_\varepsilon = -b(\varepsilon_{xx}+\varepsilon_{yy}-2\varepsilon_{zz})/2 \tag{9}$$

a_v and b being the Bir and Pikus deformation potential and ε_i are the elements of the strain tensor. Corresponding conduction band energy shift can be written as

$$\Delta E_{c,av} = (\Xi_d + \Xi_u/3)Tr\left(\overset{=}{\varepsilon}\right) \tag{10}$$

where Ξ_d is the hydrostatic deformation potential and Ξ_u is the sheer deformation potential.

Similarly approach may be used to estimate the eigenenergies of the valence band for uniaxial strain considering the Bir and Pikus 4×4 Hamiltonian resulting in a band splitting at the zone centre as equals to $2\sqrt{Q_\varepsilon + R_\varepsilon}$ where

$$R_\varepsilon = \frac{\sqrt{3}}{2}b(\varepsilon_{xx}-\varepsilon_{yy}) - id\varepsilon_{xy}$$

The overall effect of the forgoing bulk state band structure causes change in band gap energy and effective mass tensors in the stained in the nanowire material and influences the $T_{BTBT}(E)$ significantly.

2.3 OFF State Current Model

The subthresold mode of conduction occurs when the top of the valence band of the intrinsic channel ($E_{V,\text{channel}}$) falls below the bottom of the n$^+$ conduction band at the source ($E_{C,\text{source}}$) following which the energy pass window disappears and the carrier tunneling is prevented due to forbidden gap of the intrinsic channel. However, whenever a midgap trap exists and occupied by a hole with adequate thermal energy to overcome the barrier of potential energy E_t=($E_{C,}$source-$E_{V,\text{channel}}$), can tunnel from source to the intrinsic channel. The suthresold transmission probability that a hole may tunnel can be expressed as $P_{sub} = \exp\left[-E_t(\frac{1}{kT}+\frac{1}{kT^t})\right]$ where kT^t is the swing of the tail-like trap distribution. So the trap assisted BTBT can be computed in similar way as that of I_{on}. The expression for trap assisted BTBT as computed from Landauer's formula is

$$I_{off} = \frac{2q}{\text{h}}T_{BTBT}(E)P_{sub}$$
$$\ln\left[\frac{\left(1+\exp\left(\frac{E_{C,\text{source}}-E_{FS}}{kT}\right)\right)\left(1+\exp\left(\frac{E_{C,\text{source}}-E_t-E_{FD}}{kT}\right)\right)}{\left(1+\exp\left(\frac{E_{C,\text{source}}-E_{FD}}{kT}\right)\right)\left(1+\exp\left(\frac{E_{C,\text{source}}-E_t-E_{FS}}{kT}\right)\right)}\right] \tag{11}$$

The complete expression for both OFF state and ON state may be obtained by combining eq. (4) and (11).

3 RESULTS AND DISCUSSIONS

We compare the output characteristics obtained from the proposed quasi analytical ballistic model under different stress condition in Fig. 3 while the strain influence on drain current with respect to gate to source voltages are studied in Figs. 4 and 5. We have taken the uniaxial stress of -2GPa and biaxial of 2GPa and the appropriate deformation potentials and stiffness constants values are taken from Ref [6, 7]. Remarkable increase in drain current is obtained in the case of biaxial strain. This is due to the fact that both biaxial tensile stress and uniaxial compressive stress shift the valence band energy, but lowering of conduction band can be achieved with biaxial stress only causing maximum reduction of band gap energy. Moreover, the uniaxial stress offers lesser impact on the I_d-V_d curves as is found in Fig. 3.

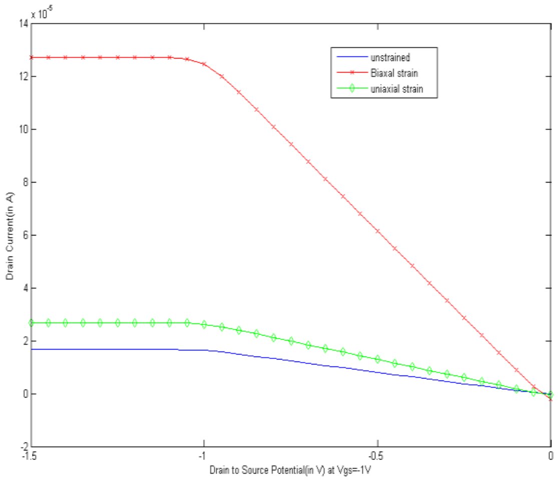

Fig. 3. Drain-current versus drain-voltage characteristics for stained and unstrained conditions. All analytical curves are plotted with device parameters d_{ch} = 10 nm, t_{ox} = 1.5 nm, e_d = 25 mev, kt^1 = 25 mev, and ε_{ox} = 25ε0.

The threshold voltage is also reduced as a consequence of lowering the conduction band with the biaxial stress as can be seen from the I_d-V_g characteristics shown in Figs. 4 and 5.

From Figs. 4 and 5 it is also found that the biaxial stress improves the SS significantly. The biaxial stress also lowers the effective mass along the channel direction due to band warping and thus tunneling probability increases.

From the results obtained in our theoretical model it can be inferred that biaxial stress applied in the perpendicular direction of the transport will improve the Ion to Ioff ratio significantly. It may be concluded by noticing that the tensile biaxial stress perpendicular to the transport is difficult to obtain in real devices. However, such a stress configuration can be attained in a vertical NW transistor [7].

For validating our model we compare the model with the experimental works of [8, 9] and a close agreement of results is achieved.

3 CONCLUSION

We have investigated the effect of strain on the performance of a ballistic nanowire TFET developing a current model applicable for both ON state and OFF state of the device. The analysis shows that ON current of a strained device improves significantly upon application of biaxial strain relative to the unstrained material while retaining the low OFF current. The threshold voltage can also be reduced due to the lowering of conduction band by the biaxial strain. The developed model can be helpful for investigating other device performance parameters such as gain conductance, gate capacitance etc. and suitability of strained TFET for various low power analog and digital applications.

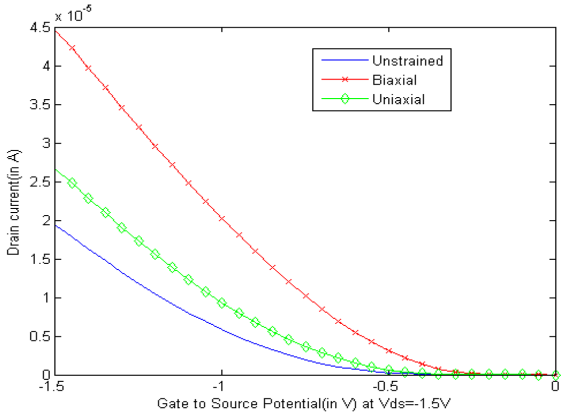

Fig. 4. Drain-current versus gate-voltage characteristics for stained and unstrained conditions.

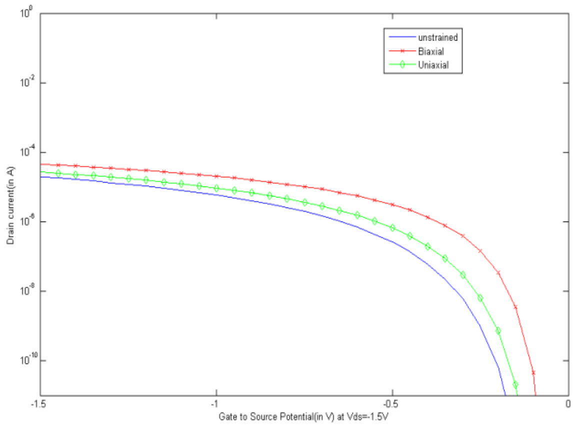

Fig. 5. Drain-current versus gate-voltage characteristics in the semilog scale for stained and unstrained conditions.

REFERENCES

[1] A. Seabaugh and Q. Zhang, 2010. Low- voltage tunnel transistors for beyond CMOS logic, Proc. IEEE, vol. 98, no. 12, pp. 2095-2110.

[2] K. Boucart and A. Ionescu, 2007. Double-gate tunnel FET with high-k gate dielectric, IEEE Trans. Electron Devices, vol. 54, no. 7, pp. 1725-1733.

[3] F. Mayer, C. Le Royer, J.-F. Damlencourt, K. Romanjek, F. Andrieu, C. Tabone, B. Previtali, and S. Deleonibus, 2008. Impact of SOI, Si1-xGexOI and GeOI substrates on CMOS compatible performance, in IEEE IEDM Tech. Dig., pp.1-5.

[4] A. S. Verhulst, W. G. Vandenberghe, K. Maex, and G. Groeseneken, 2007. Tunnel field-effect transistor without gate-drain overlap, Appl. Phys. Lett., vol. 91, no. 5, pp. 053102-1-053102-3.

[5] S. Datta, 2015. Quantum Transport: Atom to Transistor, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press.

[6] Y. Sun, S. E. Thompson, T Nishida, 2010. Strain Effect in Semiconductors:Theory and Device Applications, Springer Science, NewYork.

[7] F. Conzatti, M. G. Pala, D. Esseni, E. Bano, and L. Selmi, 2012. Strain-Induced Performance Improvements in InAs Nanowire Tunnel FETs, IEEE Trans. Electron Devices, vol. 59, no. 8, pp. 2085-2091.

[8] L. Knoll, Q. Zhao, A. Nichau, S. Trellenkamp, S. Richter, and A .Schäfer, 2013. Inverters with strained Si nanowire complementary tunnel field-effect transistors, IEEE Electron Device Lett., vol. 34, no. 6, pp. 813-817.

[9] Q. T. Zhao, W. J. Yu, B. Zhang, M. Schmidt, S. Richter, D. Buca, R. Luptak, A. Fox, K. K. Bourdelle, and S. Mantl, 2011. Tunneling Field-Effect Transistor with a Strained Si Channel and a Si0.5Ge0.5 Source, ESSDERC 2011, vol. 41, pp. 251-254.