Impact of surrounding force on the performance of vertical-stacked (110) Ge-MC-NWFETs

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INTRODUCTION: 3D stacked Gate-all-around (GAA) NWFETs have been proposed as a potential alternative to planar MOSFETs as the device dimensions shrink for excellent electrostatic control and high robustness and layout compactness [1]. Meanwhile, Germanium NWFETs and Ge/Si core/shell heterostructure NWFETs are considered to have high transport performance for the important higher mobility [6]. In order to demonstrate the strain effect on the cross-sectional distribution of the spatial resolved mobility of 3D-vertical-stacked Ge Multi-Channel NWFETs which have been rarely studied, we built a finite element solver based on continuum elastic model [3] to calculate the strain distributions caused by various strength of surrounding force under different surrounding conditions. A significant difference of hole concentration distributions under anisotropic material Silicon surrounding and isotropic material HfO_2 gate insulator is observed.

SIMULATION METHOD AND RESULTS: Based on the classic elastic theory, the strain tensors are calculated by minimizing the total elastic strain energy U [3], [4]:

$$U_{total} = U_{Ge} + U_H - \int_L F_i u_i dl$$

$$U_{Ge} = \frac{1}{2}\iint_{Ge} ds\{D_1(\varepsilon_{xx}^2 + \varepsilon_{yy}^2) + D_2(\frac{a_z}{a_{Ge}} - 1)^2$$

$$+ D_3\varepsilon_{xx}\varepsilon_{yy} + D_4(\varepsilon_{xx} + \varepsilon_{yy})(\frac{a_z}{a_{Ge}} - 1)$$

$$+ D_5\varepsilon_{xy}^2 + D_6(\varepsilon_{xx} + \varepsilon_{yy})\varepsilon_{xy}\}$$

$$U_{H-Si} = \frac{1}{2}\iint_{Si} ds\{D_1^{H-Si}(\varepsilon_{xx}^2 + \varepsilon_{yy}^2) + D_2^{H-Si}(\frac{a_z}{a_{Si}} - 1)^2$$

$$+ D_3^{H-Si}\varepsilon_{xx}\varepsilon_{yy} + D_4^{H-Si}(\varepsilon_{xx} + \varepsilon_{yy})(\frac{a_z}{a_{Si}} - 1)$$

$$+ D_5^{H-Si}\varepsilon_{xy}^2 + D_6^{H-Si}(\varepsilon_{xx} + \varepsilon_{yy})\varepsilon_{xy}\}$$

$$U_{H-HfO_2} = \frac{1}{2}\iint_H ds\{D_1^{H-HfO_2}(\varepsilon'^2_{xx} + \varepsilon'^2_{yy}) + D_2^{H-HfO_2}\varepsilon'^2_{zz}$$

$$+ D_3^{H-HfO_2}\varepsilon'_{xx}\varepsilon'_{yy} + D_4^{H-HfO_2}(\varepsilon'_{xx} + \varepsilon'_{yy})\varepsilon'_{zz} + D_5^{H-HfO_2}\varepsilon'^2_{xy}\}$$

D is elastic modulus for all materials which should be modified for Germanium and Silicon material for different orientations. Fig.4 gives the modified modulus. The band structures are calculated by using 6×6 Bir-Pikus k • p Hamiltonian [5].

Fig.1 (c1), (d1) show the strain energy distribution with HfO_2 as surrounding material when the force is 1Gpa while Fig.1(c2), (d2) show that with Silicon as surrounding condition. When the same force is introduced, the Ge/Si heterostructure is much more influenced and the strain energy is larger in the shell while the strain energy is larger in the core under HfO_2 circumstance. Both cases are symmetric along xy direction despite a little difference between middle and boundary. The HfO_2 have a more obvious difference. Fig. 2 gives the strain tensors of HfO_2 and Ge/Si conditions, strains ε_{xx}, ε_{yy} are compressive and strains ε_{xy} are tensile. All the strains have xy symmetry. Strains along 45^o are larger while the strains along 135^o are smaller than average value. The strain tensors ε_{xx} and ε_{yy} are larger under Ge/Si condition than HfO_2 condition while the ε_{xy} is larger for HfO_2. Fig. 3 shows valence band of both cases. Similar to previous work [2], the energy is raised especially for the valence band states v_1 which is very important for the valence band edge. The Ge/Si heterostructue changes the band more than HfO_2 case. Fig. 4 shows the cross-section hole distribution when various force strength are applied, the 45^o direction has the largest hole concentration and the asymmetry between the boundary (y<5) and the middle (y>5) has a result in the asymmetry of hole population which is also larger near the boundary. The asymmetry is obvious under HfO_2 condition than Ge/Si heterostructure because of the isotropic property of HfO_2 material and the anisotropic property of both Germanium and Silicon materials. Ge/Si heterostructure have larger concentration than HfO_2 insulator according to the band structure.

CONCLUSION: The simulation shows the asymmetry hole density vertically when surrounding force is applied and shall surely have an influence on the spatial mobility. Ge/Si heterostruture weakens the asymmetry impact compared with HfO_2 surrounding and have much larger band influence. This work demonstrates the advantage of Ge/Si heterostruture and gives guide for future analysis and 3D device design.

References:

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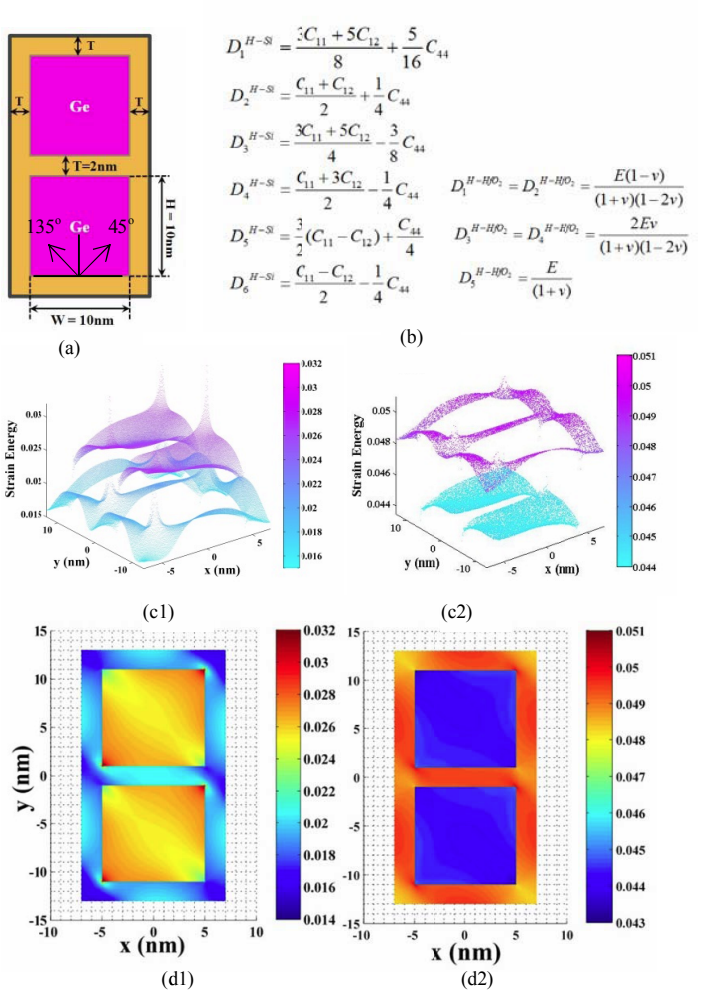

Fig.1 (a) Schematic view of 3D structure of the rectangle cross sectional shaped MC-NWFETs: the transport direction is (110). (b) The modulus been used. (c)3D and (d) cross sectional strain energy distribution for the two structures. (1) is HfO_2 surrounding and (2) is Ge/Si heterostrucute case.

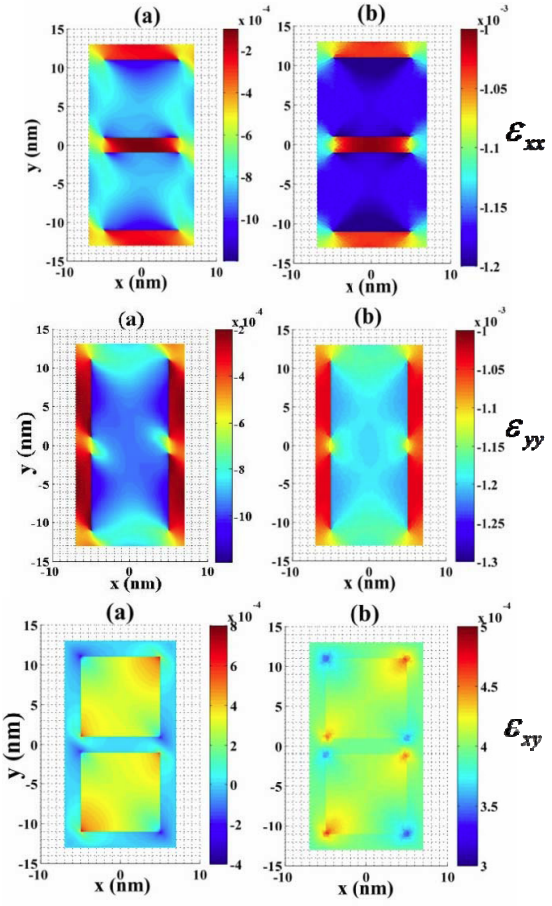

Fig.2 Schematic view of strain tensors Exx， Eyy, Exy on the x-y cross section for both (a) HfO_2 (b) Ge/Si surroundings when 0.1Gpa force is introduced.

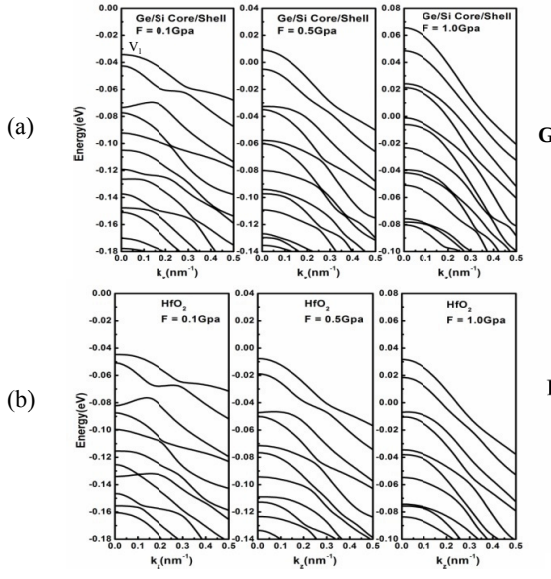

Fig.3 Valence band of (a) Ge/Si heterostruture and (b) HfO_2 gate insulator.

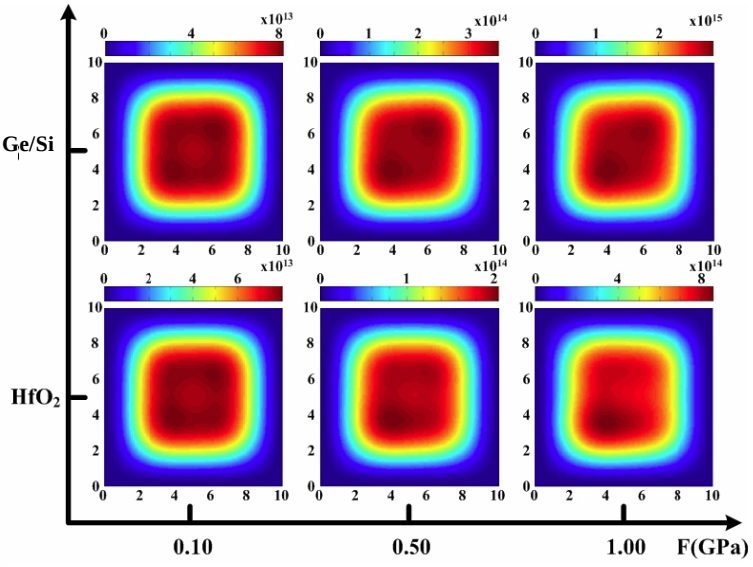

Fig.4 Hole density spatial distribution. The surrounding force is set to be 0.1Gpa, 0.5Gpa and 1.0Gpa. $V_G = 0V$.