Performance Evaluation of Uniaxial- and Biaxial-Strained $In_{(x)}Ga_{(1-x)}As$ NMOS DGFETs

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***Abstract*— For the first time, the performance of uniaxial- and biaxial- strained InxGa1-xAs NMOS Double Gate FETs (DGFET) with (111) and (001) orientations are thoroughly investigated under ballistic transport, taking into account non-parabolic full band structure, quantum effects, band-to-band tunneling (BTBT) and short-channel effects (SCE). The real and complex band structures for different composition, uniaxial and biaxial (tensile and compressive) strain are calculated using the local empirical pseudo-potential method (LEPM). In this paper, by varying strain conditions and orientations for the different materials, the best performing strained $In_xGa_{1-x}As$ materials are identified.**

InGaAs, NMOS Double gate FETs, Uniaxial strain, Biaxial strain, leakage current, drive current, Band-to-Band Tunneling, Quantum Ballistic Transport.

I. INTRODUCTION

Due to their small Γ-valley electron mass, III-V materials are being investigated as high mobility (μ) channel materials for high performance NMOS [1-3]. The main advantage of a semiconductor with a small transport mass is its high μ and injection velocity. However, these materials also have a very low density of states (DOS) in the Γ-valley, which tends to greatly reduce the inversion charge and hence reduce drive current. Furthermore, the very high μ III-V materials like InSb, have a much smaller direct bandgap (Eg) which gives rise to very high BTBT leakage. They also have a high dielectric constant and hence are more prone to SCE. $In_xGa_{1-x}As$ is a very promising candidate for future NFETs because it allows for a very good tradeoff between the excellent transport properties of InAs and the low leakage of GaAs [4,5]. In this paper, we have thoroughly investigated and benchmarked nanoscale DG NFETs with channel materials composed of InxGa1-xAs with varying composition, under different strain conditions with different orientations. By varying strain conditions and orientations for the different materials the best devices are identified. The simulations are performed under ballistic transport taking into account non-parabolic full band structure, quantum effects, BTBT and SCE.

II. DEVICE STRUCTURE AND SIMULATION METHODOLOGY

A. Quantum Ballistic Transport

The device structure simulated is shown in Fig. 1. The devices were built on (001) and (111) orientations and channel orientations are with respectively (100) and (11$\bar{2}$). Gate is 15nm long, channel is 5nm thick, gate oxide is 0.7nm thick, and V_{DD} is 0.7V. Due to the small effective mass in the Γ-valley, the quantization and the small DOS causes the inversion charge to populate the higher (X- and L-) valleys, which cannot be neglected. We include all the valleys, Γ-, X- and the L-, for the III-V materials. Non-parabolic E-k relationship is taken into account in all valleys. The drive current for the device is calculated using a ballistic transport model [6].

B. Modeling Band to Band Tunneling (BTBT)

We have developed a BTBT model which takes into account full bandstructure, direct and phonon assisted indirect tunneling, quantum confinement effect, non-uniform electric field (non-local) and strain induced enhanced/suppressed tunneling in semiconductors. In this model, the tail of electron wavefunction penetrating into the Eg [7] is modeled using the complex bandstructure (Fig. **Error! Reference source not found.** (a)), and used to evaluate the interband matrix elements between conduction band (CB) states and valence band (VB) states. Fig. 2 (b) shows the different possible transitions from VB to CB such as Γ_V-Γ_C, Γ_V-L and Γ_V-Δ. Minimum off leakage current limited by BTBT ($I_{OFF,BTBT}$) is defined as the intersection between drive current (I_{ON}) and BTBT leakage current (I_{BTBT}) . The entire I_{ON} and I_{BTBT} curves in Fig. 2 (c) horizontally move together as threshold voltage is changed by adjusting workfunction of gate metal, thus this intersection is universal minimum leakage point that this DGFET structure can ever reach.

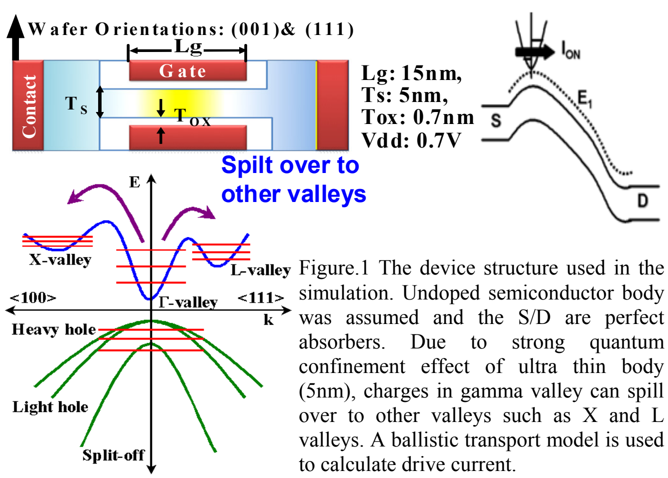
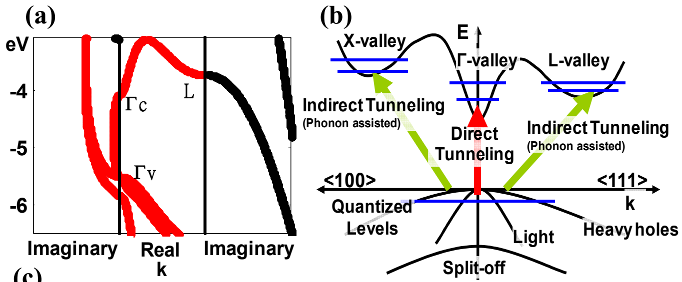


Figure.1 The device structure used in the simulation. Undoped semiconductor body was assumed and the S/D are perfect absorbers. Due to strong quantum confinement effect of ultra thin body (5nm), charges in gamma valley can spill over to other valleys such as X and L valleys. A ballistic transport model is used to calculate drive current.



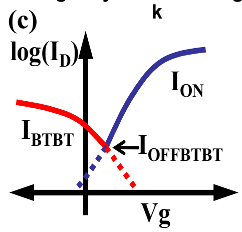


Figure. 2 (a) Complex band structures (E-k) of GaAs obtained by LEPM. Real Band: Center, Imaginary Band: Left and Right. (b) All Possible (Direct and Indirect) Tunneling Paths, Γ-Γ, Γ-X and Γ-L, are captured by the model. (c) The Off current is assumed to be limited by the BTBT.

C. *Strained Band Structure (Real and Complex)*

Since BTBT process requires the movement of electron in the bandgap, it is important to predict the E-k relationship in the bandgap where k vector becomes complex number (Fig. **Error! Reference source not found.** (a)). LEPM [8] is used to obtain the real and complex bandstructure. Fig. 3 shows the band shifts of $In_xGa_{1-x}As$ under 4% uniaxial and biaxial (tensile and compressive) strains with (001) / (111) orientations

III. Simulation Results

A. *Bandgap, the Γ-L Separation, Effective Mass and Tunnel mass:*

Application of strain can strongly modify the Eg of a material. Fig. 4 (a), (b) shows the Eg of the different 5nm thin $In_xGa_{1-x}As$ as a function of uniaxial / biaxial (compressive / tensile) strains and orientations. With quantization, due the small mass of the electrons in the Γ-valley, the carriers start occupying the high L- and X- valleys. Hence, in III-V materials, apart from the Eg, the separation between the Γ- and L-valley ($\Delta E_{\Gamma L}$) is a very important parameter in determining the transport. Fig. 5 shows $\Delta E_{\Gamma L}$ under different strain/orientation conditions. Due to strong non-parabolicity in the Γ-valley, transport effective mass is bigger in thin layers than in bulk material. Fig 6 shows transport effective mass after quantization. Tunnel mass (m_{Tunnel}) determines how well electron and hole penetrate into bandgap and cause BTBT leakage. Tunnel mass is strongly modified with application of strain. Fig. 7 shows Tunnel mass in different conditions.

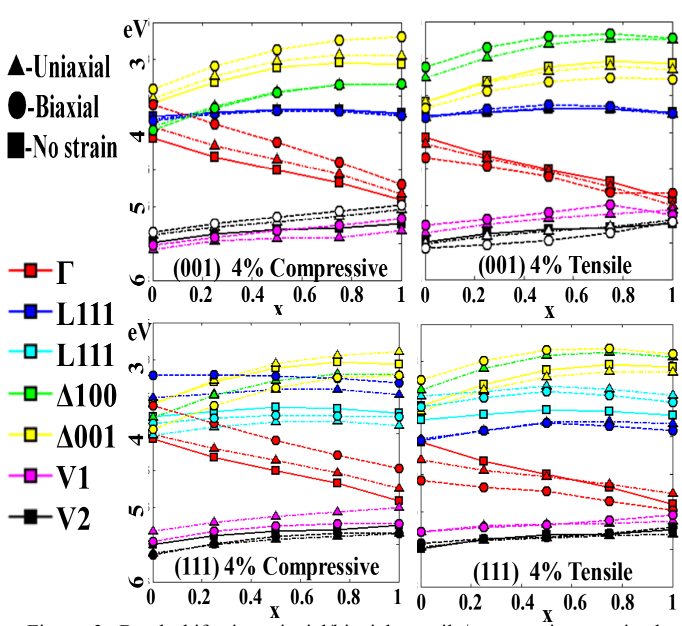


Figure 3. Band shifts in uniaxial/biaxial, tensile/compressive- strained $In_xGa_{1-x}As$ as a function of In composition, x with (001) / (111) orientations obtained by local empirical pseudo-potential method. Uniaxial strains are applied along channel directions.

B. *I_{ON}, I_{OFF} and Delay with Strain Engineerig*

Device simulation results for L_G=15nm, T_{OX}=0.7, T_S=5nm, V_{DD}=0.7V (I_{OFF}=10^{-7}A/um) are shown in Figs. 8 (I_{ON}), 9 (I_{OFF}) and 10 (Delay). All the unstrained $In_xGa_{1-x}As$ compositions, except GaAs, have at least 30% higher I_{ON} (>4.2mA/um) and 3.5 times shorter delay (<55fs) than 4% biaxial tensile strained Si. Despite of its small bandedge effective mass (0.024 m_0), InAs does not show significantly better performance than all other InGaAs compositions because of its small DOS, severe DIBL and strong non-parabolicity in Γ-valley. The strong non-parabolicity in the Γ-valley flattens the differences in effective masses after quantization. Furthermore, unstrained InAs have smallest bandgap (0.33eV), leading to too high $I_{OFFBTBT}$. I_{ON} and delay of unstrained GaAs suffers from electron population in L-valley. Ion and Delay of GaAs can be noticeably improved

Biaxial	Bi	Tensile	T
Uniaxial	Uni	Compressive	C
ex) BiT : Biaxial Tensile Strain			

$\Delta E_{L\Gamma}=E_L-E_\Gamma$

X: $In_xGa_{1-x}As$

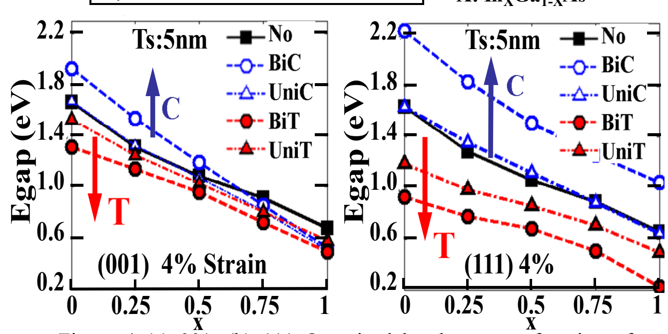


Figure 4 (a) 001, (b) 111 Quantized bandgap as a function of x (In_xGa_{1-x}) in 5nm film. Compressive strain increases bandgap.(111) strains strongly modify bandgap.

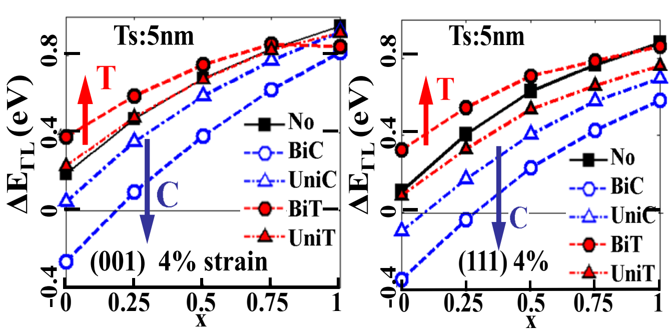


Figure 5 (a) 001 (b) 111 Γ-L Separations as a function of x (In_xGa_{1-x}) in 5nm film. Tensile strains widen the separation. In both cases 4% strain is applied..

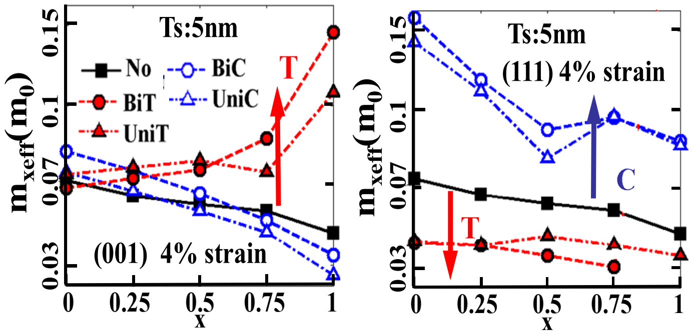


Figure 6 (a) 001 (b) 111 Transport mass (mx) as a function of x (InxGa1-x) in 5nm film. On (111) orientation, compressive strain increases mass.

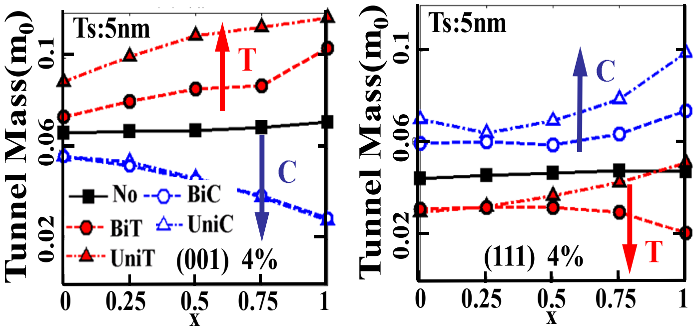


Figure 7 (a) 001 (b) 111 Tunnel mass as a function of x (In_xGa_{1-x}) in 5nm film. On (111) Orientation, compressive strain increases mass, while on (001), it reduces mass.

by tensile strains due to increase in $\Delta E_{\Gamma L}$. Without application of strain, only GaAs(001) and $In_{0.25}Ga_{0.75}As$(001) meet leakage spec. of 0.1μA/μm because of their large E_g (>1.3eV) and m_{Tunnel} (>0.06m_0). However, for (111) orientation, 4% biaxial compressive strain significantly increases E_g and m_{Tunnel}, thus, as in Figs. 9 (b) $I_{OFFBTBT}$ can be lowered below 0.1μA/μm for all the materials. As the tradeoff for lower leakage, (111) biaxial compressive strain lowers I_{ON} by increasing transport mass and reducing $\Delta E_{\Gamma L}$.

IV. Best Channel Materials and Strains

Based on our simulation results, GaAs(001), $In_{0.25}Ga_{0.75}As$(001) and $In_{0.75}Ga_{0.25}As$(111) are selected as the best channel materials. Figs. 11 (a) (I_{ON} vs. $I_{OFFBTBT}$) and (b) (Delay vs. $I_{OFFBTBT}$) depict the best channel materials and how they can be improved by strain engineering. GaAs(001) has lowest $I_{OFFBTBT}$ due to its large bandgap (>1.4eV). With the biaxial tensile strain, GaAs(001) can have I_{ON} as high as InGaAs, since the strain increases $\Delta E_{\Gamma L}$ with manageable increase in $I_{offBTBT}$. $In_{0.25}Ga_{0.75}As$(001) exhibits both good I_{ON} and low $I_{OFFBTBT}$ because of its large bandgap (>1.4eV) and large $\Delta E_{\Gamma L}$. The leakage in $In_{0.25}Ga_{0.75}As$ (001) can be further reduced with 4% uniaxial compressive strain, without significant reduction in I_{ON}. $In_{0.75}Ga_{0.25}As$(111) has excellent carrier transport properties, but it suffers large $I_{offBTBT}$. (111) biaxial compressive strain can reduce the leakage in $In_{0.75}Ga_{0.25}As$(111) below 0.1μA/μm. Considering future scaled devices with thinner body, $In_{0.75}Ga_{0.25}As$(111) may be the best material. Larger quantization effect in thinner body will further increase the bandgap of $In_{0.75}Ga_{0.25}As$(111), leading to even

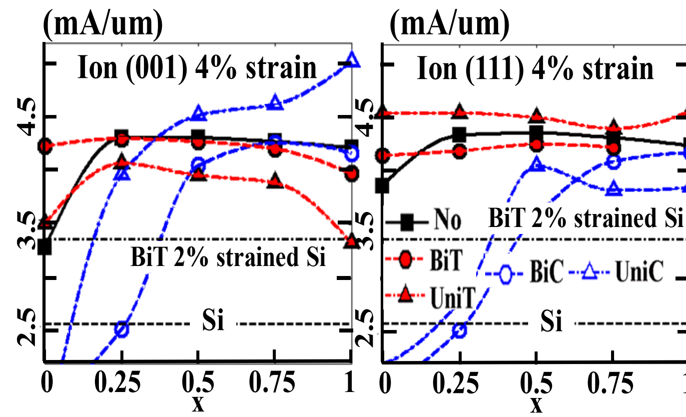


Figure 8 (a) (001) (b) (111). I_{ON} as a function of x compositions in strained $In_xGa_{(1-x)}As$ NMOS DGFET. For comparison, Ions for 2% biaxially tensile-strained (BiT) Si and unstrained Si are given.

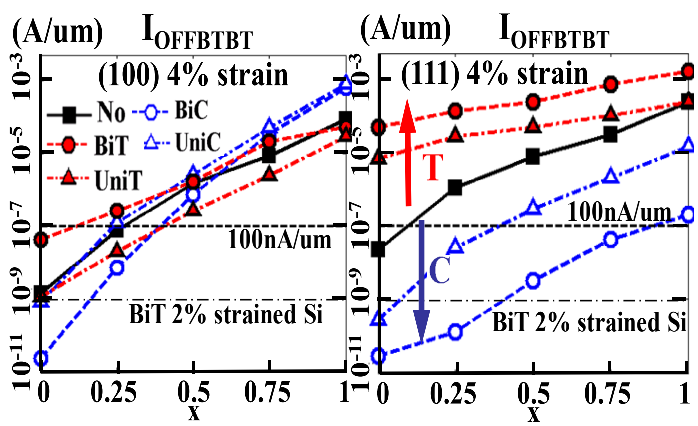


Figure 9 (a) (001) (b) (111). $I_{OFFBTBT}$ as a function of x compositions in strained $In_xGa_{(1-x)}As$ NMOS DGFET. For comparison, $I_{OFFBTBT}$ for 2% biaxially tensile-strained (BiT) Si is given.(111) biaxial compressive strain (BiC) significantly reduces $I_{OFFBTBT}$.

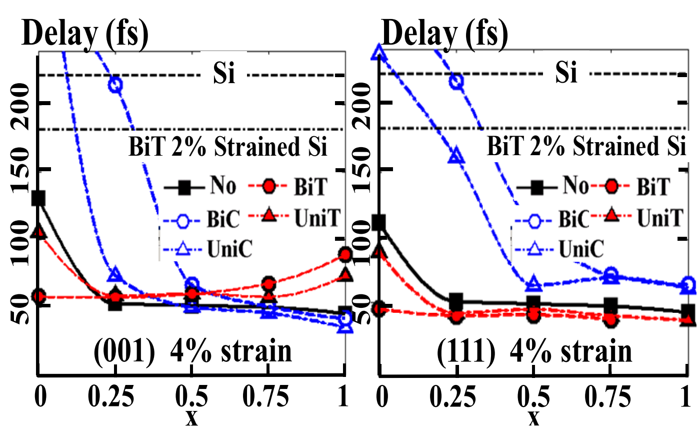


Figure 10 (a) (001) (b) (111). Delay as a function of x compositions in strained $In_xGa_{(1-x)}As$ NMOS DGFET. For comparison, delay for 2% biaxially tensile strained (BiT) Si and unstrained Si are given.

smaller leakage current. In contrast, for GaAs(001) and $In_{0.25}Ga_{0.75}As$(111), the quantization effect will result in lower I_{ON} due to reduction of $\Delta E_{\Gamma L}$.

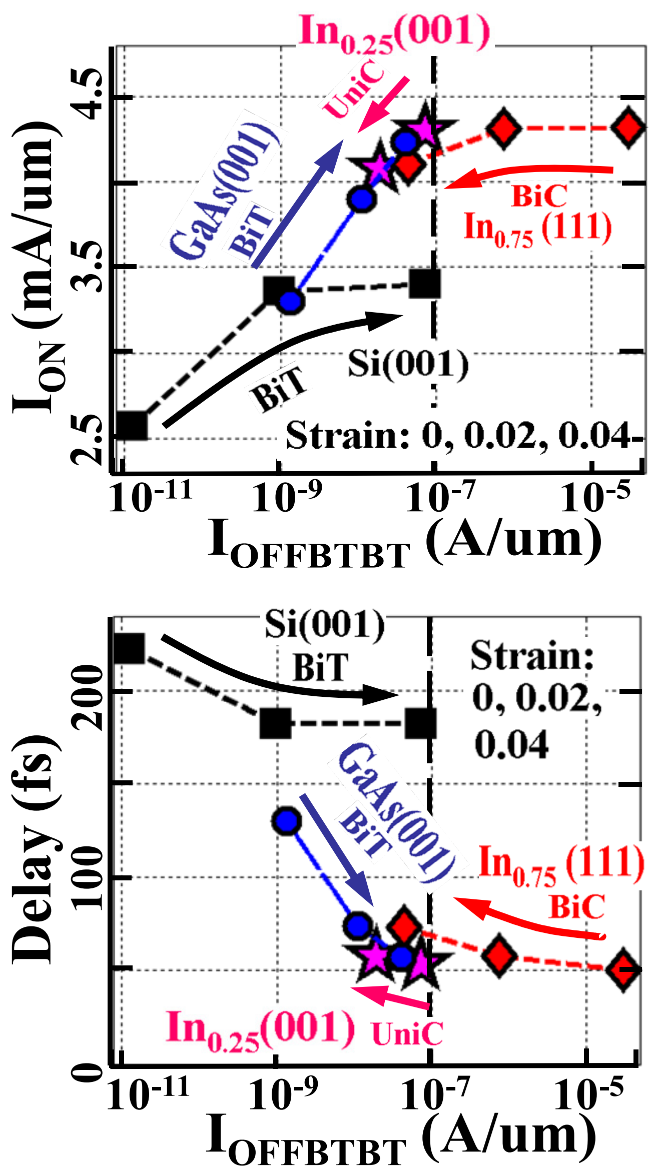


Figure 11 (a) I_{ON} vs. $I_{OFFBTBT}$ (b) Delay vs. $I_{OFFBTBT}$. I_{ON}, Delay and $I_{OFFBTBT}$ of the best performing NDGFETs with materials, biaxial strained GaAs (001), uniaxial compressive strained $In_{0\text{-}25}Ga_{0.75}As$(001) and biaxial compressive strained $In_{0.75}Ga_{0.25}As$(111). Strain levels are 0, 0.02 and 0.04. Values for biaxial tensile strained Si are given for comparison.

V. Conclusion

$In_xGa_{1-x}As$ is a very promising candidate for future NFETs. The performance tradeoffs in uniaxial- and biaxial- strained $In_xGa_{1-x}As$ NMOS DGFETs have been thoroughly investigated under ballistic transport, taking in to account non-parabolic full band structure, quantum effects, BTBT and SCE. The real and complex band structures for different composition, (001)/(111) orientation and uniaxial/biaxial tensile/compressive strain are calculated using LEPM. The main factors affecting the performance of the III-V materials, are the m_{eff}, $\Delta E_{\Gamma L}$, Eg and m_{Tunnel}. At a l00nA/um Ioff specification, 4% biaxial compressive strained $In_{0.75}Ga_{0.25}As$(111) NMOS DGFET outperforms other InGaAs compositions because of the excellent transport properties and reduced leakage current with strain engineering.

Acknowledgment

This work was supported by FCRP Materials, Structures and Device Center and Samsung Scholarship.

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