Will Strong Quantum Confinement Effect Limit Low V_{CC} Logic Application of III-V FINFETs?

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Introduction: FINFETs or Tri-Gate transistors have emerged as promising device architecture for 22nm node and beyond logic applications [1]. For sub-10nm node applications, high mobility III-V materials such as $In_{0.53}Ga_{0.47}As$ are under investigation to replace the Si channel in FINFETs to further enhance performance. The low electron effective mass results in strong quantum confinement effect in $In_{0.53}Ga_{0.47}As$ FINFETs, making them sensitive to fin width fluctuation and Fin Line Edge Roughness (LER) variation. Thus, it is imperative to quantify the sources of variation in $In_{0.53}Ga_{0.47}As$ FINFETs. In this work, we use self-consistent Schrodinger and Poisson equations to study the impact of Fin LER and L_G variations in Silicon and $In_{0.53}Ga_{0.47}As$ FINFETs. While the effect of quantum confinement makes $In_{0.53}Ga_{0.47}As$ FINFET more sensitive to Fin LER variation, the superior short channel effect in $In_{0.53}Ga_{0.47}As$ FINFETs make them less sensitive to L_G variations. The combined effect of Fin LER and L_G variations show that both Silicon and $In_{0.53}Ga_{0.47}As$ FINFETs experience the same level of variation at future technology node, with the latter still outperforming the former in terms of performance at lower supply voltage. We extend the device level variation to the circuit level by analyzing the read static noise margin (RSNM) variation of 100 Monte Carlo samples of 6T SRAM cells constructed with Si and $In_{0.53}Ga_{0.47}As$ FINFETs.

InGaAs FINFET device physics: A two-dimensional modified drift-diffusion TCAD framework is used for the simulations in this work. Fig. 1 shows the nominal device model and the physical and electrical parameters in Table 1 and 2 respectively. Drift-diffusion simulations using field-dependent mobility model (Caughey-Thomas [2]) have been calibrated and modified to include quasi-ballistic effects [3]. Fig. 2(a)-(b) depicts the transport properties of Silicon and $In_{0.53}Ga_{0.47}As$ FINFET models and compares the extracted sheet charge density, n_s and the effective velocity, v_{eff} of both the devices. At $0.5V_{CC}$, n_s of Si is 2 times higher while v_{eff} is about 4 times lower than that of $In_{0.53}Ga_{0.47}As$. The Id-Vg curves for 15nm L_G Si and $In_{0.53}Ga_{0.47}As$ FINFET are shown in Fig. 2(c). Fig. 2(c) also shows the percentage improvement in I_{ON} of $In_{0.53}Ga_{0.47}As$ with respect to Si FINFET. At $0.5V_{CC}$, we get 80% improvement in I_{ON} of $In_{0.53}Ga_{0.47}As$ over Si because of the higher effective velocity. Fig. 3(a) shows the quantum confinement effect in both the materials. $In_{0.53}Ga_{0.47}As$ being a low mass system experiences stronger confinement effects than Si. It can be seen from Fig. 3(a) that the 1st three subbands of Si participate in the transport while in $In_{0.53}Ga_{0.47}As$, the contribution comes from only the 1stsubband. The better electrostatics observed in $In_{0.53}Ga_{0.47}As$ is because of the lower S/D doping than Si (Table1) which, in turn, provides higher effective channel length (Fig.3(b)).

InGaAs FINFET variation study: Fig. 4 shows the algorithm used for LER implementation in the nominal double gate FINFET devices. Gaussian power spectral density (PSD) with RMS amplitude (Δ) of 2nm and correlation length (Λ) of 20nm is assumed for both Silicon and $In_{0.53}Ga_{0.47}As$ [4]. Apart from the Fin LER we have also included L_G variation effects (Gaussian distribution) in both the devices. Ensembles of 100 devices for each variation - Fin LER, L_G and Fin LER+L_G - are studied. Variation due to channel dopant fluctuation is ignored due to intrinsic channel doping employed in these devices. To quantify the variation impact on the electrical parameters, we performed a sensitivity analysis for Fin width (W_{FIN}) variation (without Fin LER) and L_G variation shown in Fig. 5. All the parameters show linear dependence on W_{FIN} and L_G variations. The normalized sensitivity numbers of the device parameters are given in Fig. 5. Fig. 6(a)-(c) shows the histograms of the electrical parameters of all these variant devices. Fig. 6(d) shows the σV_T for all the three cases. $In_{0.53}Ga_{0.47}As$ shows 2.3x higher σV_T for Fin LER, 2.1x lower σV_T for L_G and similar σV_T for Fin LER+L_G variations than Si. Fig. 6(e) shows the variation in the electrical transfer characteristics of both the devices with these variations. We also studied the impact of variation on the static read noise margin of the 6T SRAM cells implemented with Si and $In_{0.53}Ga_{0.47}As$ FINFETs. A cell ratio of 2 is chosen for the storage cells. Fig. 7(a) shows the best, nominal and worst case Read SNM values of Si and $In_{0.53}Ga_{0.47}As$ FINFET based SRAM cells at 300K. Fig. 7(b) shows histogram of the Read SNM values of a population of 100 6T SRAM cells with the same σRSNM (~18mV) obtained for both the devices. This implies that the variation impact on the stability of the SRAM arrays in III-V FINFETs is no worse than Si FINFETs.

Conclusion: We compared the impact of Fin LER and Lg variations in Si and $In_{0.53}Ga_{0.47}As$ FINFETs, for the first time. Better electrostatics in $In_{0.53}Ga_{0.47}As$ than in Si, due to higher effective channel length from lower SD doping in $In_{0.53}Ga_{0.47}As$, reduces Lg variation impact. Strong quantum confinement effects in $In_{0.53}Ga_{0.47}As$ FINFET make them more sensitive to Fin LER variation than Si. However, the lower sensitivity to L_G variation in $In_{0.53}Ga_{0.47}As$ FINFETs compensates for the increased variation from quantum confinement effect. Interestingly, by considering both Fin LER and L_G variations, both devices show similar sensitivity to variation. We conclude that tighter control of Fin LER in $In_{0.53}Ga_{0.47}As$ together with improved short channel immunity will make III-VFINFETs a promising device for 0.5V and below logic applications.

[1] Intel Press Release May, 2011 [2] Caughey & Thomas, Proc. of IEEE, 1967 [3] J.D.Bude, SISPAD 2000 [4] A.Asenov et al, IEEE TED 2003

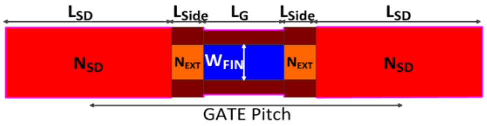

Table1: Physical Parameters of Simulation Model

Physical Parameters	Silicon	$In_{0.53}Ga_{0.47}As$
Gate Length, L_G(nm)	15	15
Fin Width, W_{FIN}(nm)	8	8
T_{OXEq}(nm)	0.7	0.7
GATE Pitch (nm)	50	50
SD Lengh, L_{SD}(nm)	25	28
L_{Side}(nm)	5	2
N_{SD}(cm^{-3})	**1e20**	**4e19**
N_{EXT}(cm^{-3})	**4e19**	**1e19**

Table2: Electrical Parameters of Simulation Model

Electrical Parameters	Silicon	$In_{0.53}Ga_{0.47}As$
I_{ON}(μA/μm)	380	690
I_{OFF}(nA/μm)	100	100
V_{TLin}(mV)	263	246
V_{TSat}(mV)	190	189
DIBL(mV)	162	125
SS(mV/dec)	84	82

Fig. 1: Physical and electrical parameters of the Nominal 2D device model. Lower SD doping in $In_{0.53}Ga_{0.47}As$ gives higher L_{eff} than Si (L_{SD} and L_{Side} adjusted to keep the Gate Pitch constant)

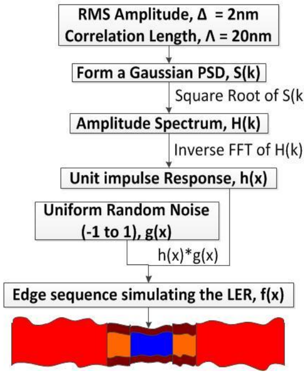

Fig. 4: Algorithm to implement LER in the 2D device model. Gaussian PSD with rms amplitude 2nm and correlation length 20nm is assumed for FinLER[4]. Gaussian distribution of 2nm rms amp. is assumed for L_G

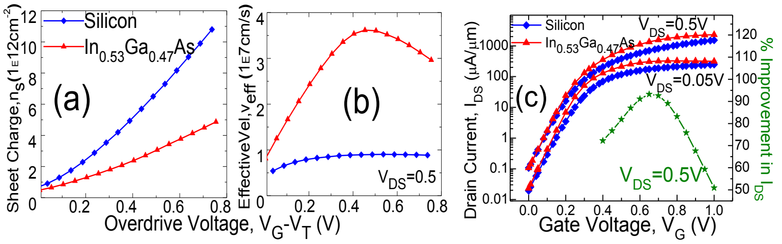

Fig. 2: (a) Sheet Charge density, n_s and (b) effective velocity, v_{eff} comparison. n_s of Si is twice of $In_{0.53}Ga_{0.47}As$ while v_{eff} of $In_{0.53}Ga_{0.47}As$ is 4 times of Si at V_{CC} of 0.5V, (c) IdVg characteristics of the 15nm Nominal device. At V_{CC} 0.5, $In_{0.53}Ga_{0.47}As$ gives 80% improvement in ON current because of higher veff.

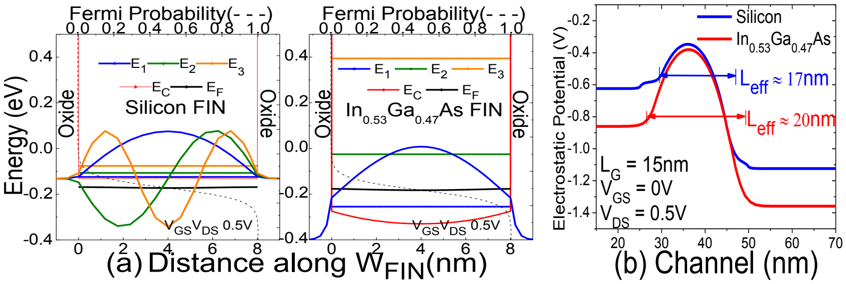

Fig 3: (a) Schrodinger-Poisson model used to capture Quantum Confinement & subband formation. At V_{GS} &V_{DS} 0.5V first 3 and 1st subband in Si and $In_{0.53}Ga_{0.47}As$ fins are occupied respectively. (b) Electrostatic Potential along the channel length shows higher effective channel length of $In_{0.53}Ga_{0.47}As$ than in Si.

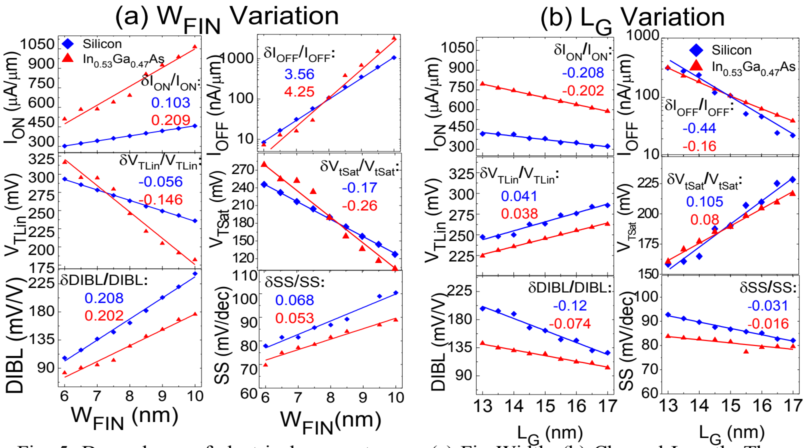

Fig. 5: Dependence of electrical parameters on (a) Fin Width, (b) Channel Length. The normalized sensitivity values are also given in the respective plots.

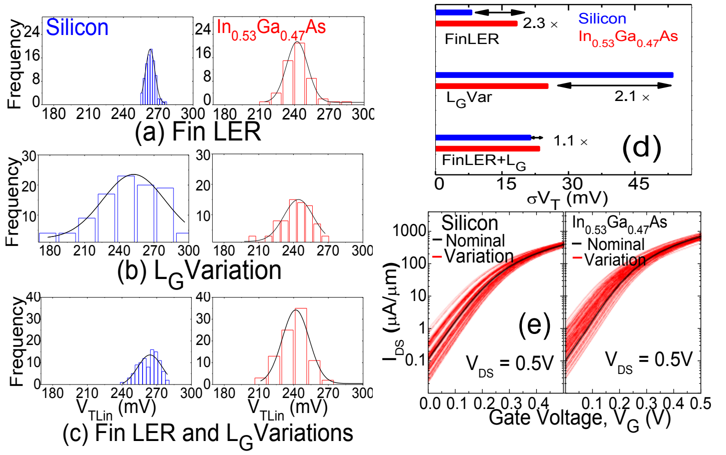

Fig. 6: Histograms of V_{TLin} of Monte Carlo samples each with (a)Fin LER, (b) L_G, (c) Both Fin LER and L_G variations (d) sigma V_T for all the three cases, (e) Variation in Id-Vg of Si and $In_{0.53}Ga_{0.47}As$. Interestingly, including both the variations gives similar sigma V_T in the two devices. This is because the lower sensitivity to L_G variation in $In_{0.53}Ga_{0.47}As$ FINFETs (2.1x) compensates for the increased variation from quantum confinement effect due to Fin LER (2.3x).

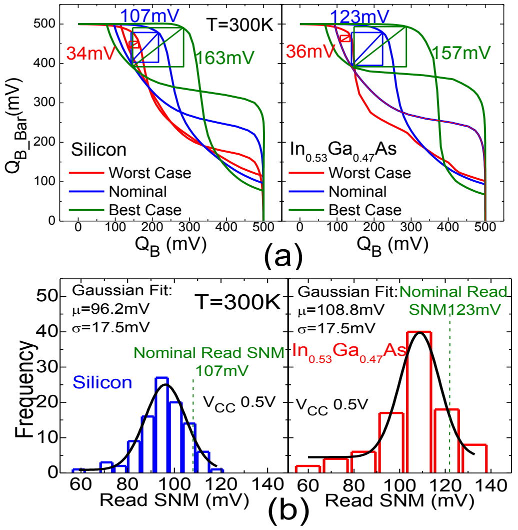

Fig.7:(a)Comparison of Read SNM of best, nominal and worst case 6T SRAM cell at 300K. (b) Histogram of RSNM. Sigma V_T due to variation of both Fin LER and L_G are same giving similar sigma of RSNM for both the devices.