Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 458-459

A Comprehensive Study of Hot-Carrier Behaviors with Consideration of Non-Local, Series Resistance, Quantum, and Temperature Effects in Multi-Gate FinFETs

P-3-27L

Jin-Woo Han, Donggun Park* and Yang-Kyu Choi
Dept. of EECS, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea
*Device Research Team, Semiconductor R&D Division, Samsung Electronics Co., Kyunggi-Do 449-711, Korea
Email:jinu0707@nobelab.kaist.ac.kr, Phone: +82-42-869-5477, Fax: +82-42-869-8565

ABSTRACT

Hot-carrier effects in FinFETs are investigated in terms of the fin width and a temperature. A non-local effect and the series resistance were found to be evident features that suppress hot-carrier effects for a narrower fin. Below 14nm of fin, bandgap widening caused by quantum confinement is an additional factor reducing multiplication. Unlike conventional hot-carrier behavior, the impact ionization rate is increased with the temperature increment for wide bias ranges, which degrades the hot-carrier reliability. The decrease of the energy relaxation mean free path is attributed to the increase of impact ionization at high temperatures.

INTRODUCTION

Multiple-gate FinFETs have been considered as attractive technology to substitute for a planar MOSFET due to their superior short channel characteristics and their conventional fabrication process [1]. Although the excellent substrate current (I_{SUB}) models have been developed for the planar MOSFET, a model for FinFETs has not been developed. Thus, a modeling of impact ionization in a FinFET is timely as well as essential. As the circuit operation temperature increases, hot-carrier effects (HCE) should be carefully examined to verify the usability of the classical I_{SUB} model.

In this study, a body-tied FinFET was fabricated for measuring I_{SUB}. A refined analytical I_{SUB} model is derived and then compared to measured data. The unique features of a non-local effect, series resistance, and effective bandgap widening are investigated. Finally, the temperature (T) dependence of HCE is evaluated for the first time.

EXPERIMENTAL

The fabrication process details were reported elsewhere [2]. A schematic of a body-tied FinFET is shown in **Fig. 1**. The gate length is 70nm, the fin widths are in a range of 4nm to 140nm, and the gate oxide thickness is 1.7nm. Device simulation is carried out with an energy balance model by SILVACO. High temperature characteristics were measured with a hot-chuck system from 300K to 450K. Hot-carrier stress bias was chosen as the worst-case condition, V_G at $I_{SUBpeak}$. All measured data are from n-channel devices.

RESULTS AND DISCUSSIONS

A. Fin width dependence of impact ionization in FinFET:

FinFETs suffer from high parasitic resistance ($R_{S/D}$) due to the narrow width of the S/D extension region. The increase of $R_{S/D}$ can cause a potential drop across the extension region suppressing the peak electric field (E_{peak}) as shown in **Fig. 2**. Although E_{peak} may be identical, the field gradient can be different as shown in **Fig. 3**. The electric field has been commonly modeled as $E(x) \propto \exp(x/\lambda)$, in which the characteristic length λ must be related to the gradient of $E(x)$. As λ becomes smaller as the body thickness (fin width) decreases, a steeper $E(x)$ can be explained by the smaller λ of the narrower fin [3]. According to the non-local energy balance model, the energy of electrons lags behind the electric field under rapidly increasing $E(x)$ [3]. This implies that the electrons can be less energetic if the E_{peak} is identical but that field changes rapidly as shown in **Fig. 4**. In order to investigate the impact of the series resistance and non-local effect on HCE, the impact ionization parameter B_i is extracted as shown in **Fig. 5**. To verify the effect of the series resistance on B_i, an extrinsic resistor R_{ext}=3kΩ was intentionally connected to the S/D of W_{Fin}=100nm. The extracted B_i becomes larger at a narrower fin and at a device with an extrinsic resistor, which implies I_{SUB} reduction. In an earlier study of the non-local effect, B_i was modeled as $B_i=B_0(1+\lambda_e/\lambda)$, where λ_e is the energy relaxation mean free path [3]. However, this model much deviates from the measured data especially below W_{Fin}<60nm as shown in **Fig. 6**. A refined empirical model is proposed. It considers a series resistance as $B_i=B_0(1+W_{ref}/W_{Fin})(1+\lambda_e/\lambda)$, where W_{ref} is a fitting parameter. The proposed model with W_{ref}=10nm is well matched to the measured data. Following the widely used derivation for substrate current [4], the multiplication factor can be derived as

$$M-1=\frac{A_i}{B_0}\frac{\lambda}{\xi(\lambda+\lambda_e)}(V_D-V_{Dsat})\exp\left(-\frac{B_0\xi(\lambda+\lambda_e)}{V_D-V_{Dsat}}\right),\ \xi=\left(1+W_{ref}/W_{Fin}\right) \quad (1)$$

and model of eq.(1) fits to the measured data well as shown in **Fig. 7**. In W_{Fin}<14nm, effective bandgap widening by quantum confinement can further suppress impact ionization as shown in **Fig. 8** [5]. The factors influencing HCE are summarized in **Fig. 9**.

B. Temperature dependence of impact ionization in FinFET:

Generally, I_{SUB} is expected to decrease as the operating T increases. As T increases, λ_e decreases due to phonon scattering, therefore I_{SUB} should be reduced. Although the phonon scattering is clearly observed, however, the carrier multiplication is increased in FinFETs as shown in **Fig. 10**. It is important to note that if λ_e is reduced, the carrier energy gain can be reduced while the non-local carrier heating is relaxed. For $\lambda \gg \lambda_e$ or local impact ionization, $B_i=B_0(1+\lambda_e/\lambda)$ is insensitive to variation in λ_e thus reduced carrier energy results in I_{SUB} suppression. For $\lambda \ll \lambda_e$ or non-local impact ionization, however, a decreased B_i with a decreasing λ_e dominates I_{SUB} behavior at an elevated T. Thus, the non-local carrier heating effect is gradually quenched, which increases impact ionization. As λ or W_{Fin} decreases, T dependency becomes sensitive to variation of λ_e as shown in **Fig. 11**. The positive T dependency is observed for an overall gate bias, and it tends to be weaker as V_D increases as shown in **Figs. 12** and **13**. At a lower V_D, the most carriers have insufficient energy for impact ionization, and a small amount of carriers in high energy tail responds susceptibly to the quenched non-local effect at high T. The transition point to the new regime is extrapolated to V_D=3.8V which is found to be W_{Fin} independent. This voltage is comparable to the breakdown voltage, therefore, positive T dependence holds in all interested biases. In hot-carrier stress, a narrower fin shows better robustness to degradation, and an elevated T stress accelerates degradation as shown in **Fig. 15**. The hot-carrier lifetime is projected for different T as shown in **Fig. 16**. The high T stress shows worse lifetime compared to its room T counterpart, the deviation tends to increase as stress V_D reduces. As the technology developments provide shorter dimensions and lower supply voltages, the acceleration stress should be set at a high temperature in order to project hot-carrier lifetime accurately.

CONCLUSIONS

Hot-carrier effects in FinFETs were investigated considering two aspects; fin width and temperature. As the device scales down, the increased effect of the series resistance and non-local carrier heating suppress the hot-carrier effects, and effective bandgap widening can further decrease the hot-carrier at ultrathin body regimes. However, as the operating temperature increases, non-local carrier heating tends to be quenched. As the driving voltage scales and the operating temperature increases, hot-carrier degradation is accelerated. Therefore acceleration stress should be carefully set at a high temperature.

ACKNOWLEDGEMENT

This work was supported by Samsung Electronics Co., Ltd.

REFERENCES

[1] Y-K Choi *et. al.*, *IEDM Tech. Dig.*, p.421, 2001. [2] T. Park *et. al.*, *Symp. VLSI Tech*., p.135, 2003. [3] K. Taniguchi *et. al.*, *IEDM Tech. Dig.*, p.335, 1994. [4] P. Ko *et. al.*, *IEDM Tech. Dig.*, p.600, 1981. [5] C. R. Bologesi *et. al.*, *IEEE Tran. on Elec. Dev. Dig*., p.826, 1999.

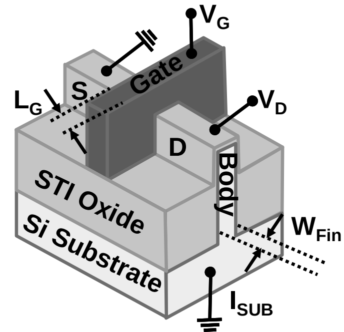

Fig. 1. Schematic device structure of a multiple-gate body-tied FinFET. As the Si body (fin) is tied to the substrate, the impact ionization current (I_{SUB}) can be measured by its body contact.

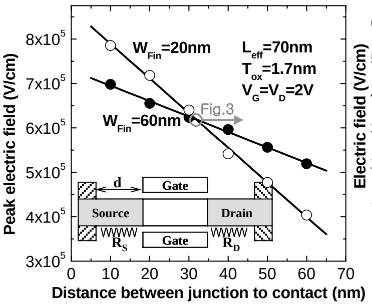

Fig. 2. Simulation prediction of the peak electric field (E_{peak}). At a narrower fin, a parasitic voltage drop through the thin extension region gives rise to a significant decrease of E_{peak}.

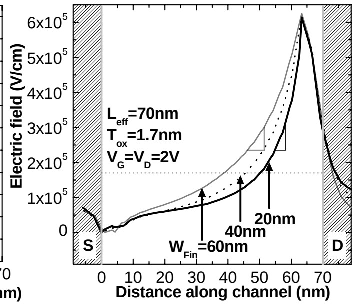

Fig. 3. Simulation prediction of the electric field for various W_{Fin}. Although E_{peak} is identical, the field gradient of a narrower fin is steeper than that of a wider fin.

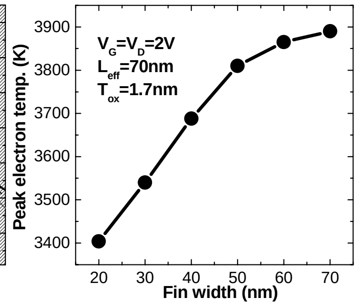

Fig. 4. Simulation prediction of the peak electron temperature for various W_{Fin} values showing identical E_{peak}. As W_{Fin} decreases, The T_{peak} decreases regardless of the same E_{peak}, which results from non-local carrier heating.

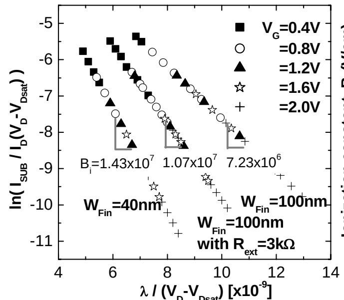

Fig. 5. $\ln(I_{SUB}/I_D(V_D\text{-}V_{Dsat}))$ versus $\lambda/(V_D\text{-}V_{Dsat})$ characteristics for impact ionization parameter, B_i, extraction, where λ is a characteristic length. B_i is larger at a narrower W_{Fin} and a higher series resistance.

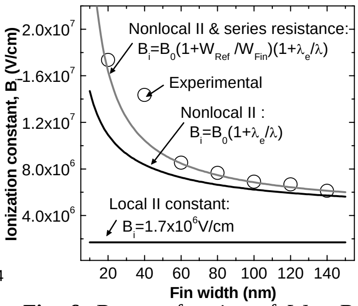

Fig. 6. B_i as a function of W_{Fin}. B_i model considered nonlocal effect in [3] much deviates much from that measured one. However, the B_i model considering the non-local effect as well as the series resistance is well matched to the measurement.

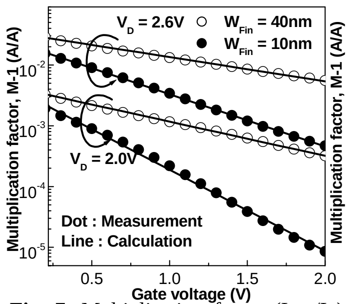

Fig. 7. Multiplication factor (I_{SUB}/I_D) for different W_{Fin} and V_D. A smaller M-1 at a narrower W_{Fin} results from a larger B_i due to significant series resistance and non-local effect. Calculation of Eq. (1) fits extremely well to the measurement data.

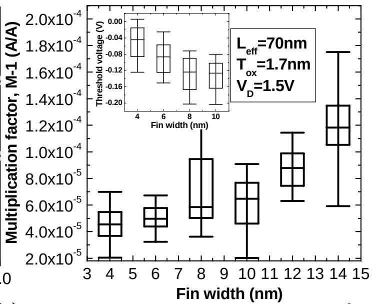

Fig. 8. M-1 at V_G@$I_{SUBpeak}$ for W_{Fin}<14nm. As W_{Fin} deceases, M-1 decreases. Effective band gap widening can be an additional mechanism suppressing impact ionization.

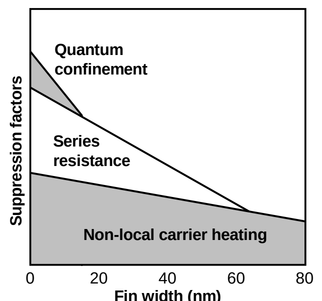

Fig. 9. As the device scales, the fin width should be reduced in order to avoid short-channel effect. Therefore, the non-local effect, parasitic voltage drop, and bandgap widening can result in the suppression of hot-carrier effect.

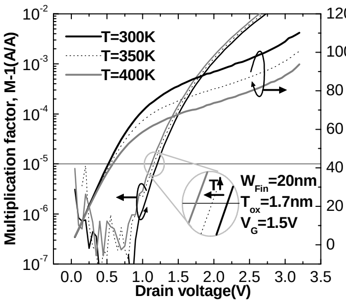

Fig. 10. M-1 and I_D as a function of V_D. While the increased phonon scattering is obvious for a decreased drain current, the increased II results from the T-induced energy relaxation length reduction.

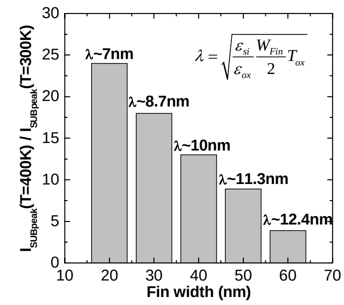

Fig. 11. $I_{SUBpeak}$ increment as a function of the fin width. As λ or W_{Fin} decreases, T dependency becomes sensitive. λ_e is known to 110nm [3]. Because λ is much smaller than λ_e, As $\lambda \ll \lambda_e$, non-local carrier heating is obvious.

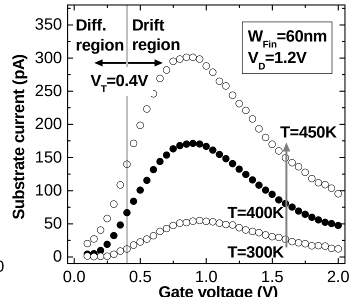

Fig. 12. Temperature dependence of the substrate current at a low V_D=1.2V. Unlike the conventional impact ionization model, I_{SUB} tends to increase with the temperature overall gate bias.

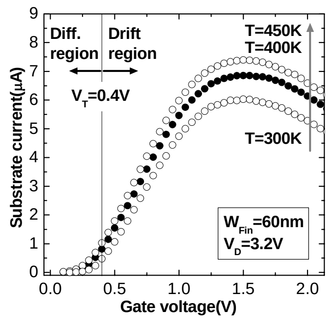

Fig. 13. The positive temperature dependence of the substrate current is still observed despite of the high V_D=3.2V, but the temperature dependency becomes weaker than the low V_D=1.2V.

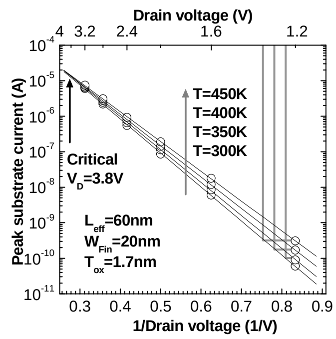

Fig. 14. T dependence of $I_{SUBpeak}$ as a function of V_D. As V_D increases, the T dependency becomes small and the extrapolated transition V_D=3.8V is larger than the breakdown voltage.

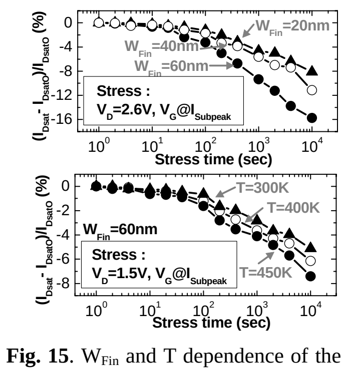

Fig. 15. W_{Fin} and T dependence of the HC degradation. A narrower fin is more robust to HC stress. Unlike traditional HC behavior, an elevated T accelerates degradation. This implies the worst stress condition should be at high T.

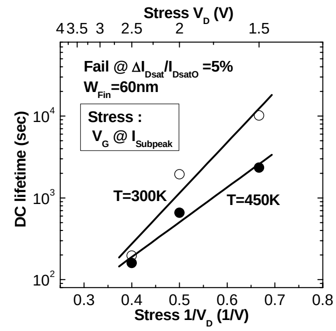

Fig. 16. DC lifetime by HC stress for different stress T. The lifetime can be overestimated if the test is done at room T. This miss-estimation tends to be a severe problem as the operation voltage scales