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B-2-3

Comparison of Sub-Bandgap Impact Ionization in Deep-Sub-Micron Conventional and Lateral Asymmetrical Channel nMOSFETs

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1. Introduction

Impact ionization in silicon nMOSFETs for drain voltages (V_D) well below the bandgap voltage of silicon has received widespread attention [1,2,3]. Substrate currents (I_{SUB}) for drain voltages down to 0.6V [1] and floating body effects in SOI devices down to 0.8V [2] were reported. This would imply that the impact ionization induced operational and reliability issues in nMOSFETs will continue to deca-nano meter device generations.

Based on Monte Carlo simulations it was suggested that various modes of electron-electron interactions resulting in the high energy tail (HET) of the electron energy distribution are responsible for some electrons to have more energy than that gained from the lateral electric field (E_{LAT}) [3,4]. An anomalous increase of the gate voltage at which the I_{SUB} peaks (V_{Gpeak}) which can not be explained by HET is presented. We have also compared the sub-bandgap impact ionization in CONventional (CON) and Lateral Asymmetrical Channel (LAC) nMOSFETs of channel length 100nm. An enhancement of the increase in V_{Gpeak} is found in the LAC devices. Based on the results presented we propose quantization of inversion layer as an additional energy gain mechanism for the electrons.

2. Experimental

The MOSFETs used in this study had a channel length of 100nm and gate oxide thickness of 3.6nm. Both CON and LAC MOSFETs were fabricated on the same wafer for fair comparison. The fabrication procedure of the devices are described in detail elsewhere [5]. Fig. 1 shows the simulated channel doping profiles of the CON and LAC MOSFETs used in this study and reveals the nonuniform channel doping for the LAC devices. Fig. 2 shows the output characteristics of the CON and LAC devices.

3. Results and Discussions

The I_{SUB}-V_G characteristics of the devices were measured for V_D down to 0.85V. Fig. 3 shows the I_{SUB}-V_G plots for CON and LAC for the lowest V_D investigated and the LAC shows much lower I_{SUB} than the CON. In fig.4 the V_{Gpeak} is compared. The V_T is subtracted from V_{Gpeak} to account for the difference in V_T of the two devices. The V_{Gpeak} shows expected linear behavior for V_D above 1.5V. Below 1.5V, the V_{Gpeak} is found to deviate from this and start increasing as the V_D is decreased further. For LAC the increase in V_{Gpeak} is much more pronounced for low V_D than the CON. Fig. 5 compares the ratio I_{SUB}/I_D at $I_{SUBpeak}$ for the two devices. Also shown is the ratio of $I_{SUBpeak}$ of LAC to CON. For V_D below 1.3V the ratio I_{SUB}/I_D falls off more rapidly as V_D is lowered as compared to the high V_D regime. This fall-off is less rapid for the LAC than the CON as seen from the $I_{SUBpeak}$ ratio.

Fig. 6 shows the I_{SUB}/I_D versus $1/V_D$ plot for both CON and LAC where it is seen that the data deviates from the predictions of the lucky electron model for low V_D. It was shown that Auger recombination can be an additional energy gain mechanism [6]. Fig. 7 shows the correlation between I_{SUB} and $I_D^2 I_{SUB}$ [6]. Although a great part of the data for V_D=1.5V support the Auger recombination as an additional energy gain mechanism, for low V_D such a correlation is not found. The high energy tail theories in the present form [3,4] can not explain the V_G dependence presented in fig. 4.

Figures 8, 9 and 10 show the simulated E_{LAT}, transverse field (E_{TRA}) and electron concentration respectively for V_D=0.9V and V_{Gpeak}-V_T for CON (0.48V) and LAC (0.87V). For the LAC the E_{LAT} is smaller than that for CON. The E_{TRA} near the drain becomes smaller as the V_G is increased. The effect of the increase in the positive E_{TRA} is to pull up the electrons more to the interface as shown in the fig. 10.

4. Model

Based on the results presented above we propose inversion layer quantization as an additional energy gain mechanism for the electrons. The concept is illustrated in fig. 11. The electrons in the quantized inversion layer has energy higher than the conduction band edge, E_C. But the electrons can relax to E_C near the drain junction where there is no quantized layer. As can be appreciated from fig. 11, the electrons in the quantized case effectively have a higher energy than otherwise [7]. As the V_D is reduced the energy gain from E_{LAT} decreases, which calls for stronger inversion. The enhanced V_{Gpeak} increase for LAC can be due to the lower E_{LAT} and hence the energy deficit to cause impact ionization is more. The electron concentration at the surface would increase for the CON devices too for larger V_G as illustrated in fig. 10. The electron mobility near the drain end is much smaller for the CON than the LAC because of an order of magnitude higher channel doping, fig. 1 and larger field, figures 8 and 9, near the drain [8]. This makes the secondary energy gain mechanisms less efficient in the case of CON as is evident from the more rapid fall of $I_{SUBpeak}$ for V_D below 1.3V for CON, fig. 5, right y-axis.

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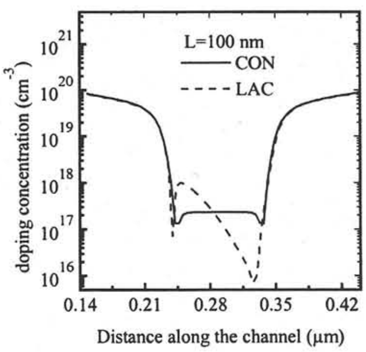

Fig. 1 Comparison of doping distribution in CON and LAC MOSFETs.

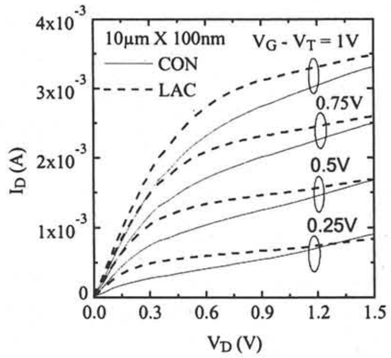

Fig. 2 I_D-V_D characteristics of the CON and LAC MOSFETs. LAC shows better saturation and higher current drive.

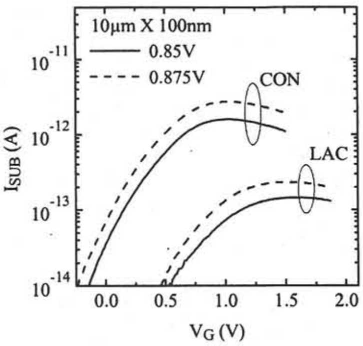

Fig. 3 I_{SUB}-V_G plots for CON and LAC MOSFETs measured for V_D well below band-gap voltage of silicon.

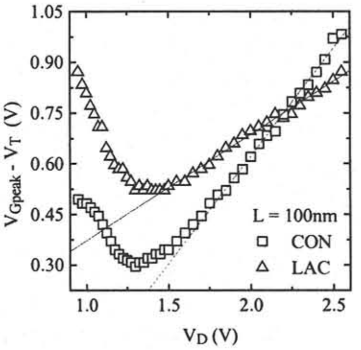

Fig. 4 Dependence of the gate voltage at which I_{SUB} peaks (V_{Gpeak}) on the V_D for CON and LAC MOSFETs.

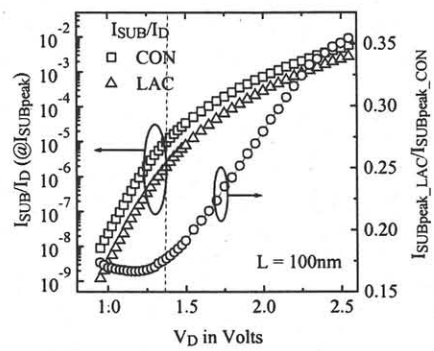

Fig. 5 Dependence of the I_{SUB}/I_D ratio on V_D. The ratio decreases rapidly below V_D of 1.3V. The ratio of I_{SUB} of LAC to that of CON is also shown.

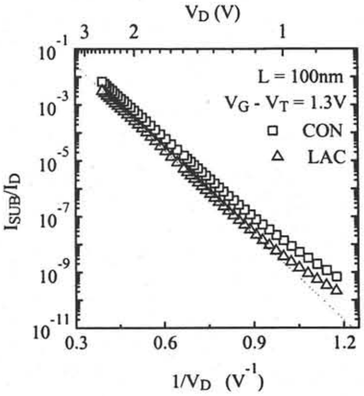

Fig. 6 The I_{SUB}/I_D ratio versus $1/V_D$ plot. At low V_D the data deviates from the straight line indicating that LEM is inadequate to explain I_{SUB} at low V_D.

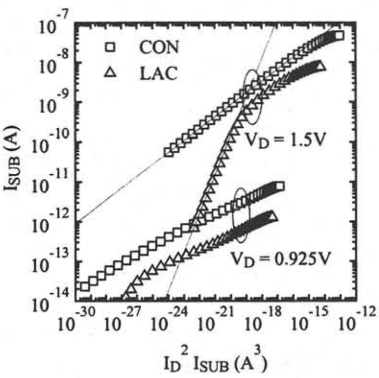

Fig. 7 I_{SUB} versus $I_D^2 I_{SUB}$ showing a power law relationship for a great part of the data for VD=1.5V for both CON and LAC suggesting Auger recombination as a possible energy gain mechanism. For low V_D this dependence is very weak.

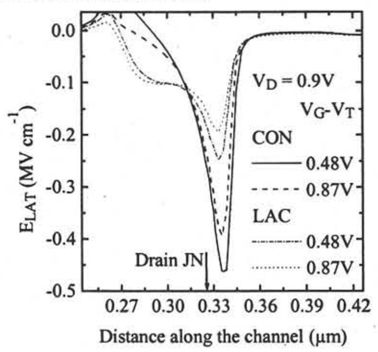

Fig. 8 The lateral electric field distribution for both the devices corresponding to the V_{Gpeak} conditions for the CON and LAC shown in fig. 4. V_{GT} = 0.48V correspond to V_{GT} peak for CON and 0.87V for the LAC.

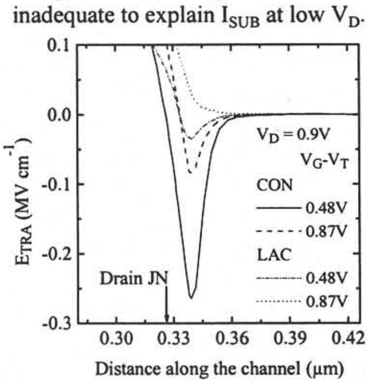

Fig. 9 The transverse field distribution for LAC and CON devices for the bias conditions described in fig. 8.

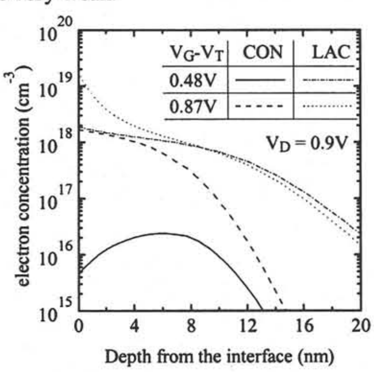

Fig. 10 Distribution of electron concentration near the drain junction for LAC and CON devices for the bias conditions described in fig. 8.

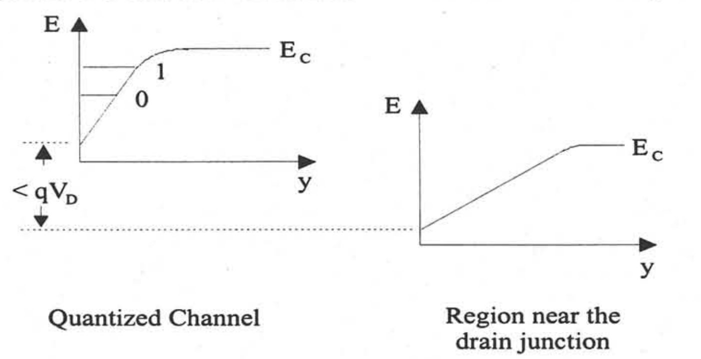

Fig. 11 Inversion layer quantization as an energy gain mechanism. In the quantized inversion layer the electrons occupy the sub-bands (marked 0 and 1). Near the drain junction the electron layer is not quantized. In this region the electrons can relax to the bottom of the conduction band resulting in an effective energy gain corresponding to the energy of the sub-band above E_C.