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Channel Length Dependence of Tunnel FET Subthreshold Swing

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I. INTRODUCTION

Unlike conventional MOSFETs, the gated p-i-n diode [1] tunnel FETs [2]–[6] have tunneling currents for both the subthreshold as well as on-region of operation. The $I - V$ characteristics show a weak positive temperature coefficient over a wide temperature range [7]. Thus, the subthreshold swing S, can be scaled to below the kT/q diffusion limit of conventional MOSFETs [8], [9]. In principle, S can be vanishingly small within a small range of gate bias V_{GS} [10], [11]. However, even with a 40mV/dec swing extremely low on-currents were observed in tunneling carbon nanotube MOSFETs [12]. Using a band-diagram approach we show that the subthreshold swing for tunnel FETs is not a constant but is strongly dependent on the tunneling barrier width, ω, and hence V_{GS}.

II. BAND DIAGRAM APPROACH

Fig. 1, shows the simulated band-diagrams for a tunnel FET (L =100 nm, t_{ox} =2 nm) as a function of V_{GS} for constant V_{DS}. The energy contours between source and drain are depicted close to the Si-SiO$_2$ interface. To a first approximation we assume constant tunneling barrier height (bandgap W_g) and effective mass m_o (it does not vary with applied bias). In this case the drain current I_{DS} depends exponentially on the barrier width, ω. From the band-diagrams in the saturation region [6] ω nearly independent of V_{DS} [10]. We then can write:

$$I_{DS}(\omega) \sim e^{-\omega} \text{ and } 1/\omega \sim V_{GS} \tag{1}$$

Thus, taking a derivative of ω with respect to $\ln(I_{DS})$ and V_{GS}, we get

$$d\ln(I_{DS}(\omega)) \sim -d\omega, \text{ and} \tag{2}$$

$$d\omega \sim -\omega^2 \cdot dV_{GS} \tag{3}$$

This implies that the *smaller* ω gets, the more difficult it becomes to *further* lower it for a *constant* dV_{GS}. Thus, from (2) and (3)

$$S(\omega) = \frac{dV_{GS} \cdot \ln 10}{d\ln(I_{DS})} \sim \frac{dV_{GS}}{-d\omega} \sim \frac{1}{\omega^2} \tag{4}$$

which is a strong non-linear function of ω, and hence V_{GS}. It is degrading with increasing V_{GS}, and hence limits I_{on}. This is confirmed by experimental results as shown in Fig. 2, where we have plotted 'spot' swing as function of V_{GS} (data from [7]). Furthermore (4) also implies that I_{DS} is decaying *faster* than exponentially and ideally, for $\omega \to \infty$, $S \to 0$, consistent with simulation predictions [10]. Thus, in principle, with a proper choice of device geometry parameters, for example with pseudomorphically strained δp$^+$SiGe layer [8], [10], I_{DS} can increase *several orders of magnitude* within a small range of V_{GS}.

III. RESULTS AND DISCUSSION

We now look at the impact of channel length L scaling on S. For a fully depleted channel and heavily doped source and drain regions, ω_o at $V_{GS} = 0$ V (assuming flat-band and constant V_{DS}) is limited by L. As L is scaled, ω_o is lowered. Thus, from (4), S is expected to *degrade* with L scaling into the ultra short channel length regime. However, as I_{on} is determined by the channel in inversion (ω <5 nm), L scaling is not expected to affect I_{on}. This is confirmed by both experimental (Fig. 3) as well as 2-D device simulations (Fig. 4) where we show the transfer characteristics as a function of L. As L is scaled, S is clearly seen to degrade at turn-off voltages while I_{on} remains almost

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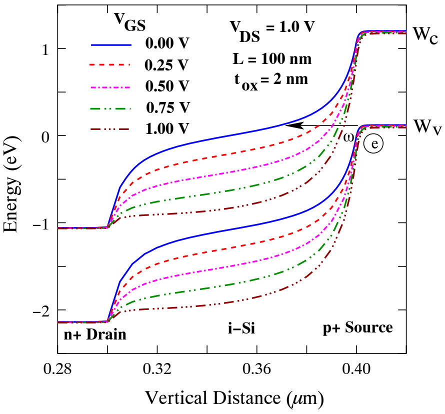

Fig. 1. Simulated band-diagrams for a tunnel FET close to the Si-SiO$_2$ interface, as a function of V_{GS}. ω lowers with increasing V_{GS}.

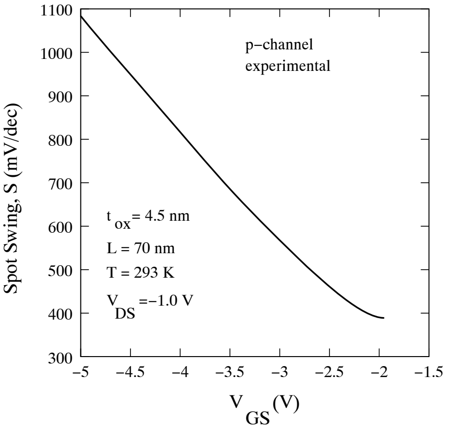

Fig. 2. Experimental ‘spot’ S as a function of V_{GS} (p-channel). S is seen to degrade with increasing V_{GS}. Note that the high value of spot ‘S’ is due to a thick oxide and doping smear-out effects.

independent of L scaling. Thus, while the characteristics of the tunnel FETs is nearly independent of channel length, L [13], [14], even for sharp and abrupt tunnel junctions, S starts to degrade with L scaling into the ultra short-channel regime. This is confirmed by both experimental as well as simulation results.

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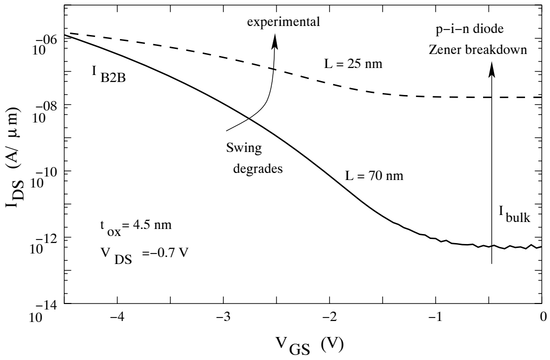

Fig. 3. Experimental p-channel transfer characteristics for L =25nm and 70nm [7]. It should be noted that the doping profile also plays a critical role in determining S.

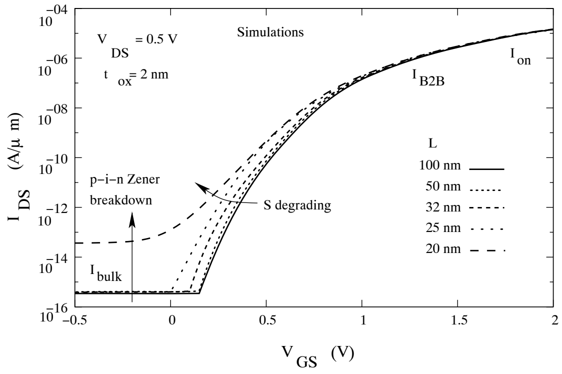

Fig. 4. Simulated n-channel transfer characteristics as a function of L. At ultra short channel lengths, S is seen to degrade with L scaling.

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