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Direct Observation of Channel-Doping-Dependent Reverse Short Channel Effect Using Decoupled C-V Technique

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A quantitative analysis of channel-doping-dependent reverse short channel effect in submicron CMOS technology is reported. The "Decoupled C-V technique" is implemented to measure the intrinsic channel capacitance (excluding the gate-to-source/drain overlap capacitance) and derive the effective channel doping concentration. In this paper, by using the Decoupled C-V technique, we report (1) direct measurement of channel-length-dependent channel doping concentration in submicron CMOS devices, (2) the dependence of reverse short channel effect on channel doping concentration, and (3) the sensitivity of reverse short channel effect in n- and p-channel MOSFETs. The channel doping concentration is measured to increase as the channel length decreases and this behavior is observed to be more significant in the higher channel doping devices. The apparent threshold channel-doping-concentration for reverse short channel effect is found to be about 3×10^{16} and $10^{17}/cm^3$ for n- and p-channel MOSFETs, respectively.

INTRODUCTION

The anomalous reverse short channel effect, i.e., the threshold voltage increases as the channel length decreases, was recently observed in the submicron CMOS technology [1-4]. From the measured increased threshold voltage, the enhanced dopant diffusion during polysilicon oxidation processing or silicidation processing is proposed to be the major cause for reverse short channel effect. The reverse short channel effect can significantly degrade the performance of CMOS circuits since the increased threshold voltage will reduce the overdrive current, particularly in the scaled power supply technology. In the scaled CMOS devices, there is a tendency in increasing the channel doping to reduce the short channel effect (From 0.5 to 0.25um technologies, the channel doping has increased from 7×10^{16} to $2 \times 10^{17}/cm^3$). It is not yet clear that the dependency of reverse short channel effect on the channel doping concentration. In this paper, by using the Decoupled C-V technique, we report (1) direct measurement of channel-length-dependent channel doping concentration in submicron CMOS devices, (2) the dependence of reverse short channel effect on channel doping concentration, and (3) the sensitivity of reverse short channel effect in n- and p-channel MOSFETs.

EXPERIMENTS

The Decoupled C-V technique, developed by Guo and Hsu [5], is to measure the intrinsic channel capacitance and derive the effective channel doping concentration from the minimum capacitance. As shown in Fig. 1(a), due to the significant portion of capacitance contributed from extrinsic gate-to-source/drain overlap in the short channel device, the calculated high frequency C-V which assumes constant channel doping along the gate covered region is dramatically deviated from the measured C-V. However, as the intrinsic channel capacitance is extracted using the Decoupled C-V method, as shown in Fig. 1(b). the measured C-V can be very well characterized by the theoretical C-V. The effective channel doping concentration, gate oxide thickness, and threshold voltage can be derived from this intrinsic channel C-V. To quantitatively measure the channel-doping-dependent reverse short channel behavior, devices with different channel implantations are fabricated. As listed in Table I and II, the channel implantation ranging from 10^{11} to $10^{13}/cm^2$ and resulting channel doping concentration from 10^{16} to $10^{18}/cm^3$. The gate oxide thickness is 14.5nm. All the devices are subjected to the Decoupled C-V measurement.

RESULTS AND DISCUSSIONS

As shown in Fig. 2, the normalized intrinsic channel capacitance (normalized to the intrinsic channel area) of short channel devices has a greater minimum capacitance than that of long channel devices. The larger minimum normalized intrinsic channel capacitance

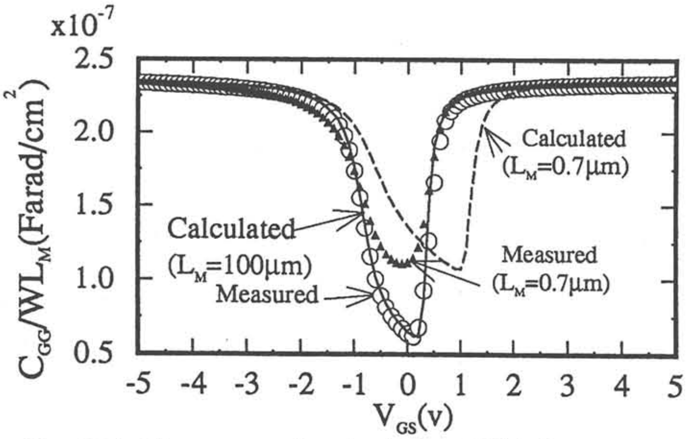

Fig. 1(a). The measured and calculated high frequency gate-capacitance vs. voltage (C-V) characteristics of long and short channel MOSFET devices

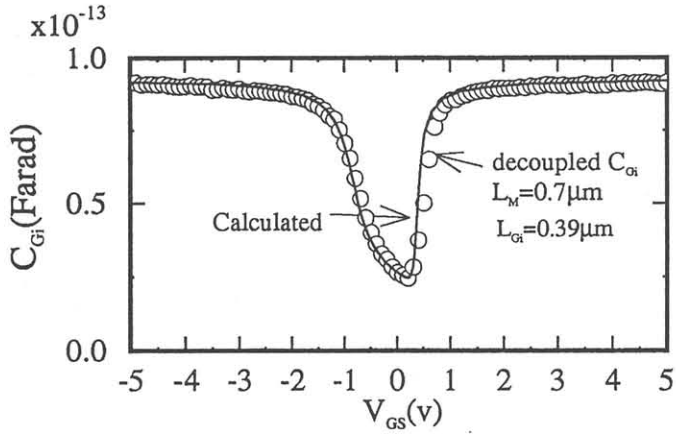

Fig. 1(b). The extracted intrinsic channel C-V and calculated C-V of short channel MOSFETs.

in short channel devices indicates a higher channel doping concentration. The enhanced channel doping concentration is observed to increase as the channel length decreases. For different channel implantations,

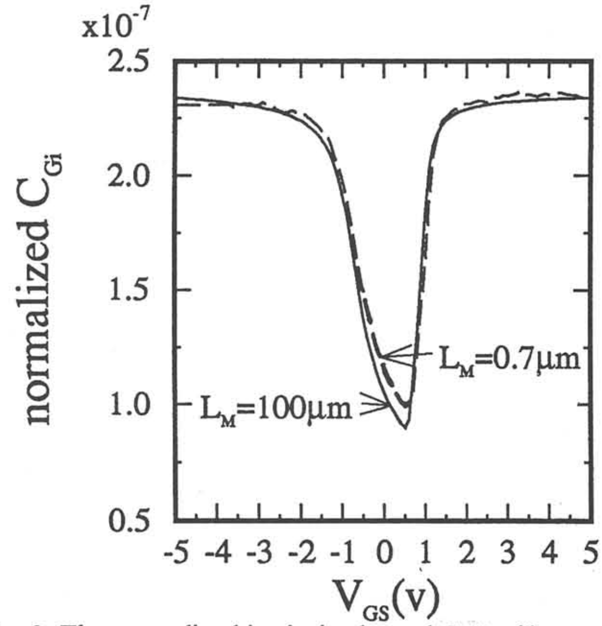

Fig. 2. The normalized intrinsic channel C-V of long and short channel MOSFETs.

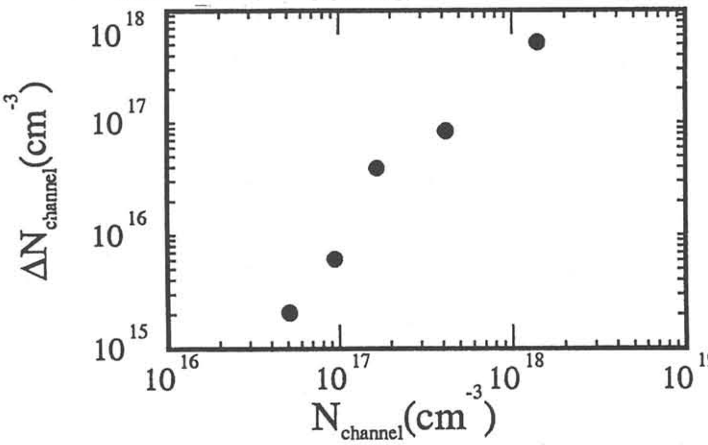

Fig. 3. The enhancement of doping concentration in short channel devices (as compared to long channel devices) as a function of channel doping concentration of long channel devices.

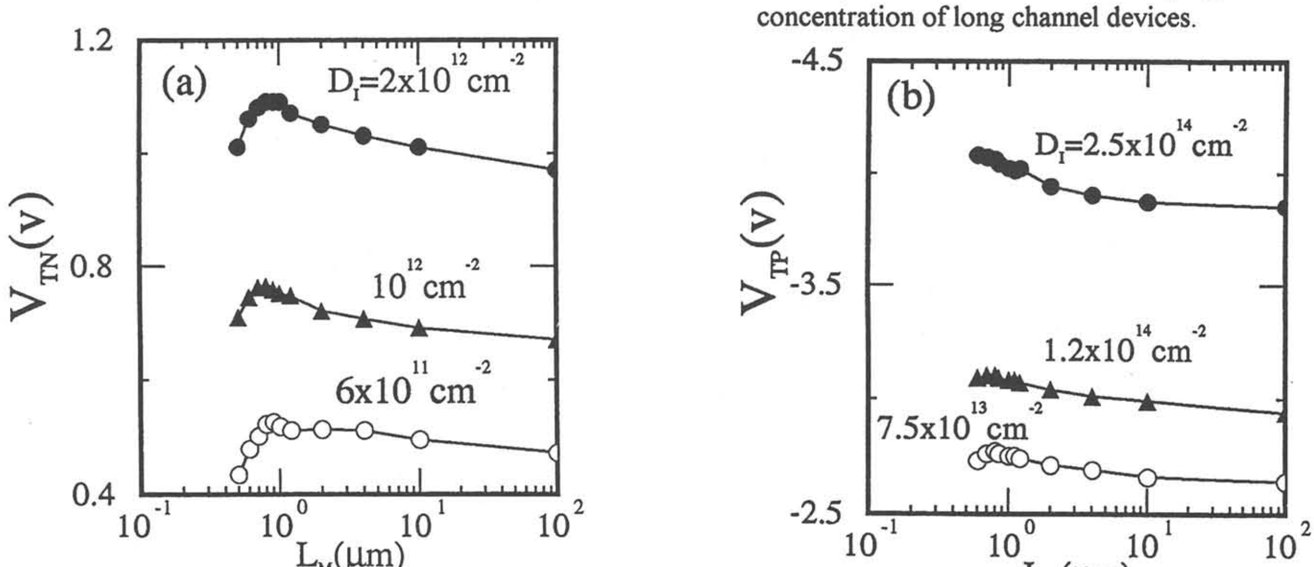

Fig.4 The threshold voltage as a function of channel lengths in (a)N- (b)P- channel MOSFETs with different channel implant doses

Table The split of channel implantation and measured effective channel doping concentration of long and short (I) N-MOSFET (II) P-MOSFET

(I)

P-well implant dose (cm^{-2})	VT adjust implant dose (cm^{-2})	Effective N_A (L_M=100μm) (cm^{-3})	Effective N_A (L_M=0.7μm) (cm^{-3})
$8x10^{12}$	$6x10^{11}$	$5.094x10^{16}$	$5.3x10^{16}$
$1.5x10^{13}$	10^{12}	$9.4x10^{16}$	$1.001x10^{17}$
$3x10^{13}$	$2x10^{12}$	$1.666x10^{17}$	$2.05x10^{17}$
$8x10^{13}$	$6x10^{12}$	$4.18x10^{17}$	$5.02x10^{17}$
$1.5x10^{14}$	10^{13}	$7.02x10^{17}$	$7.91x10^{17}$
$3x10^{14}$	$2x10^{13}$	$1.39x10^{18}$	$1.906x10^{18}$

(II)

N-well implant dose (cm^{-2})	Effective N_D (L_M=100μm) (cm^{-3})	Effective N_D (L_M=0.75μm) (cm^{-3})
$2.3x10^{13}$	$1.341x10^{17}$	$1.552x10^{17}$
$7.5x10^{13}$	$3.9x10^{17}$	$4.13x10^{17}$
$1.2x10^{14}$	$5.338x10^{17}$	$6.6x10^{17}$
$2.5x10^{14}$	$1.128x10^{18}$	$1.2x10^{18}$

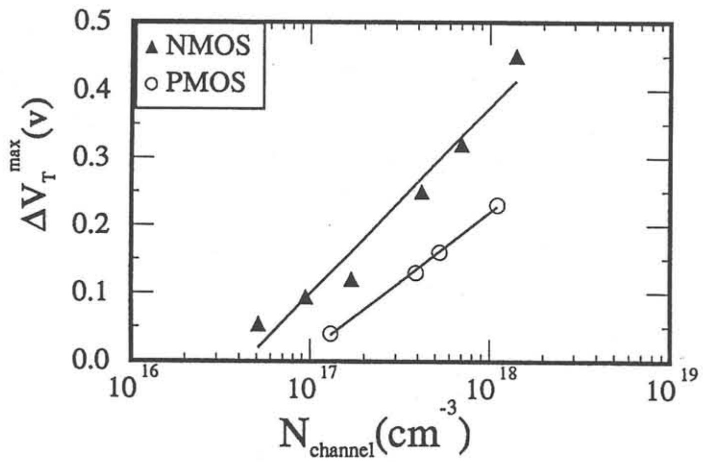

Fig. 5. The dependences of the maximum increased threshold voltage in short n- and p-channel devices (as compared to long channel devices) on the channel doping concentration.

the channel doping enhancement in short channel devices (compared to long channel devices) increases with the channel implantation doses as listed in Table I and II for both n- and p-channel devices, respectively. The dependence of the doping enhancement in short channel devices on the channel doping concentration is illustrated in Fig. 3.

The resulting reverse short channel effect due to the doping enhancement in short channel devices is demonstrated in Fig. 4. It is obviously observed that (1) the threshold voltage increases as the channel length decreases and (2) the reverse short channel effect increases with the channel doping concentration. As illustrated in Fig. 5, the reverse short channel effect of n-channel devices is more sensitive to the channel doping concentration than that of p-channel devices. The "apparent threshold channel-doping-concentration" for observing reverse short channel effect is about $3x10^{16}$ and $10^{17}/cm^3$ for n- and p-channel devices, respectively. The maximum reverse short channel effect for the doping concentration ranging from 10^{17} to $5x10^{17}/cm^3$ (which is the concentration ranges for sub-0.5um CMOS devices) are from 100 to 250mV for n-channel devices and 0 to 150mV for p-channel devices. The increased threshold voltage can greatly degrades the worst case CMOS circuit performance. To alleviate the reverse short channel effect becomes the immediate challenge in sub-0.5um CMOS technologies.

CONCLUSIONS

In summary, by using Decoupled C-V technique to quantitatively analyze the channel-doping-dependent reverse short channel effect, for the first time our study presents that (1) the direct measurement of the increased channel doping concentration as the channel length decreases, (2) the quantitative dependence of the reverse short channel effect (Vt increase) and channel doping concentration enhancement in short channel devices on the channel doping concentration, and (3) the apparent threshold of channel doping concentration for reverse short channel effect in n- and p-channel is about $3x10^{16}$ and $10^{17}/cm^3$, respectively. These findings provide the design guidelines for the control of short channel effects.

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