Direct Observation of the Lateral Nonuniform Channel Doping Profile in Submicron MOSFET's from an Anomalous Charge Pumping Measurement Results

*Steve S. Chung, S.M. Cheng, G.H. Lee and J.C. Guo**

Department of Electronic Engineering, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C.
* Submicron Lab., ERSO, ITRI, Hsinchu Industrial Park, Taiwan, R.O.C.

Abstract

This paper reports a new model and characterization of the reverse short channel effect (RSCE) as a result of the lateral nonuniform channel doping profile in submicron MOSFET's. The anomalous increase in the charge pumping current with decreasing channel length has been observed experimentally for the first time by using a charge pumping measurement. This is attributed to the enhanced nonuniform channel doping profile with the decreasing channel length as a result of the interstitial imperfections caused by OED or S/D implant. A simple and accurate model is proposed to determine the effective *lateral nonuniform doping profile* along the channel. The effective channel doping profile calculated from the new approach presents an obvious doping enhancement near the drain region of submicron devices by comparing with that of long channel devices. The simulated threshold voltages and I-V characteristics based on this profile show excellent agreement with the experimental data.

Introduction

An increase in the threshold voltage for short channel MOS devices (known as reverse short channel effect or RSCE) has been commonly attributed to the lateral nonuniform channel profile of the MOSFET's. Poly gate reoxidation [1], source/drain (S/D) implant damage [2], and silicidation [3] in submicron MOS device process have been identified as the cause for the localized enhanced dopant diffusion. However, there is still no direct evidence to show the existence of such a nonuniform lateral channel doping profile. In this work, we will show for the first time a new characterization and modeling method to explain the RSCE and directly determine the effective nonuniform lateral channel doping profile from an anomalous charge pumping measurement data.

Experimental

The devices used in this work were n-channel MOSFET's with 14nm gate oxide. The substrate doping of n-MOSFET's is uniform and has a S/D implanted with Arsenic (5×10^{15} cm^{-2}, 80kev). The basic experimental setup for a fixed base level charge pumping measurement is shown in Fig. 1 where the frequency of 1MHz is used. Shown in figure is also the local threshold voltage along the channel for devices with RSCE occurred. The charge pumping currents (I_{cp}) were measured for n-MOSFET's with various gate lengths from 0.5μm to 1.2μm and the same gate width of 50μm.

Results and Discussion

Fig.2 shows the measured charge pumping current I_{cp} along with the threshold voltage characteristics for the tested devices. According to the charge pumping (CP) theory, CP current should be proportional to the device channel length. One interesting result from Fig. 2 reveals that an anomalous I_{cp} is measured in which I_{cp} decreases with decreasing channel length (from L= 1.2μm to 0.8μm) while becomes increasing for devices down to 0.5μm. This can be supported by the following arguments. In Fig.1, if the local threshold voltage $V_T(x)$ behaves like curve B, from the beginning of CP measurement, the measured current is monotonically increasing from P_1 toward the point P_2. After that, if the high level of gate pulse V_{gh} is higher than P_2, then the CP current rises rapidly and even higher than the case of curve A of a long channel device. In other words, the characterized local $V_T(x)$ such as curve B with a hump at P_2 corresponds to a nonuniform doping along the channel as is obvious from the relationship between doping concentration and the threshold voltage formula. If for a set of devices without reverse short channel effect, its CP currents will steadily decrease with reducing channel length (Fig.3). Moreover, from the maxima of I_{CP}'s, the difference between short channel effect and RSCE can be seen from the comparison in Fig.4. We observe that the $I_{cp,max}$ increases with the decreasing of metallurgical length (L_{eff}), the $I_{cp,max}$ of the RSCE begin to deviate from the straight line at length of 0.8μm. The calculated local threshold voltages for different channel length devices are shown in Fig.5 which is as expected as shown in Fig.1. Using the charge pumping measured data in Fig.3 and by assuming a nonuniform channel doping profile which is characterized as a negative interface charge density q_{it}, the q_{it} distribution can be obtained using our previous method for interface state characterization[4]. These interface charge distributions are plotted in Fig.6(a), in which the nonuniform distribution is probed further into the channel by comparing with that of devices with lower I_{CP}'s. This result is different from some people predicted that there is a so-called characteristic length for the distribution which is a constant for the same set of devices such as the model in [5]. Fig.6(b) shows the calculated nonuniform channel doping profile along the channel for different devices. These doping profiles can be considered as the *effective* values distributed at the interface. It gives us strong evidence that the lateral nonuniform channel doping profile in a submicron device exists undoubtedly due to the OED or S/D implant damages. As such, for the simulation of the RSCE, these doping profiles can be easily implemented in the threshold voltage or drain current simulation. A threshold voltage model for RSCE can be achieved by considering Q_{it} as an extra charges on the interface (eq.3 in Table1). The simulated results of the threshold voltage shift for different channel lengths and the comparison with experimental data are shown in Fig.7(a), while the simulated I-V characteristics are compared in Fig.7(b). Very good agreements can be achieved which shows the validity of the present model.

Conclusion

In summary, by using the charge pumping method to characterize the RSCE, *for the first time* our studies show that (1) the direct observation of the nonunifrom doping profile along the channel is a result of the measured anomalous CP currents, (2) the observed nonuniform doping distribution can be regarded as a monitor for the process design, (3) the threshold voltage increases with the reducing

 0-7803-2602-4/95

channel length (or the RSCE) can be characterized as an interface charge quantitatively, (4) the same methodology is not limited to the study of conventional MOS(single drain) devices, it can be applied to any other device structures with channel implants and (4) to simulate the device V_T or drain current, the developed profile provides an easy way for device simulation applications.

Acknowledgements This work was sponsored by the National Science Council under contract *NSC83-0404- E009-101*. Device fabrication by the ERSO, ITRI, Hsinchu Industrial Park is also gratefully acknowledged.

References

[1] M. Orlowski et al., in *IEDM Tech. Dig.*, p.632, 1987.
[2] T. Kunikiyo et al., in *NUPAD IV Tech. Dig.*, p.51, 1992.
[3] C.Y. Lu et al., *IEEE EDL*, vol.10, p.446, 1989.
[4] S.S. Chung et al., Extended Abs., SISC, Dec.8-11, p.P-4.2.3, Florida, 1993.
[5] N.D. Arora et al., *IEEE EDL*, vol.13, p.92, 1992.

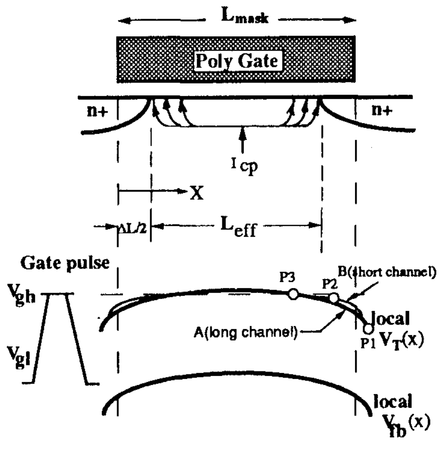

Fig. 1 Schematic of the fixed level charge pumping measurement. The hump (curve B) in the local threshold voltage curve $V_T(x)$ shows the reverse short channel effect (RSCE).

$$I_{cp}(V_{gh}) = k\int_{\frac{L_{eff}}{2}}^{L_{eff}} q_{it}(x)u[V_{gh} - V_T(x)]dx, \quad (1)$$

where

$$u(f(x)) = \begin{cases} 0 & f(x) < 0 \\ 1 & f(x) \geq 0 \end{cases}.$$

$$q_{it}(x) = a_0 + a_1x + a_2x^2 + ... + a_nx^n \quad (2)$$

$a_0, a_1, a_2, ...$ and a_n can be obtained from [4].

$$\Delta V_T = Q_{it}/C_{ox}L_{eff}W \quad (3)$$

Table 1 Formulae used in the present new model

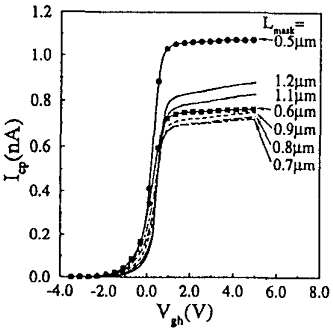

Fig.2 The measured CP currents for the tested devices.

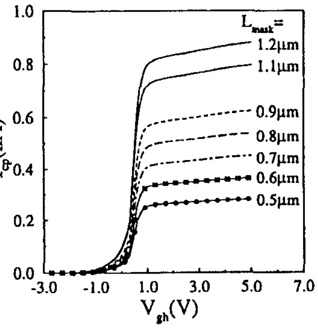

Fig.3 The normal CP currents for devices without the RSCE.

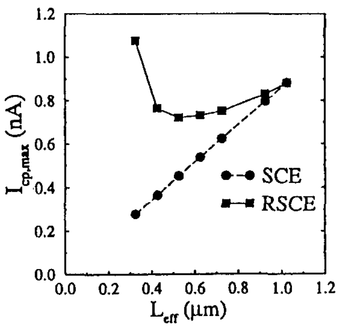

Fig.4 Values of $I_{cp,max}$ versus L_{eff} in which RSCE shows anomalous characteristics.

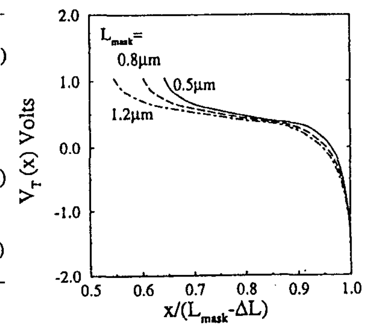

Fig.5 The calculated local threshold voltages for different channel length devices.

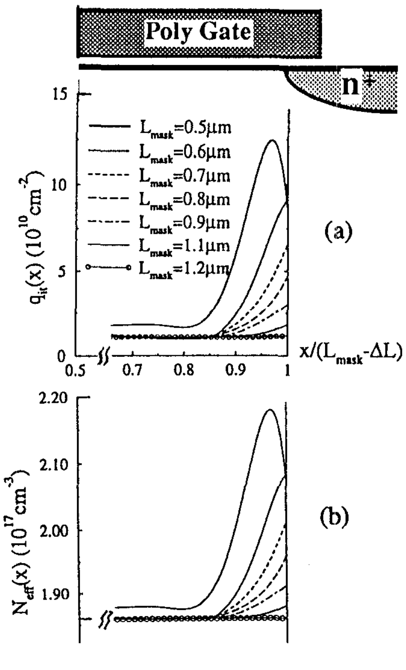

Fig. 6 (a) Extracted interface charges distribution along the channel.
(b) Extracted effective lateral nonuniform profile along the channel.

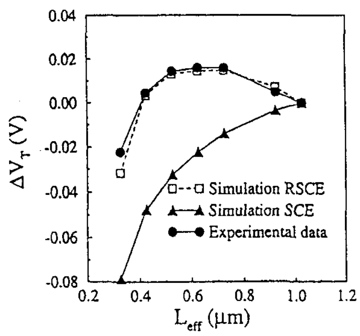

Fig.7(a) The comparison of threshold voltage shift between the simulation and experiment.

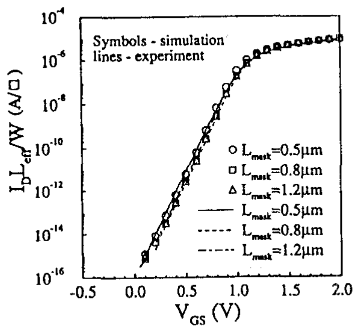

Fig.7(b) The comparison of I-V curves between simulation and experiment.