C-V Characteristics and Analysis of Undoped Gate-All-Around Nanowire FET Array

Rock-Hyun Baek\textsuperscript{1}, Chang-Ki Baek\textsuperscript{2}, Sang-Hyun Lee\textsuperscript{1}, S. D. Suk\textsuperscript{3}, M. Li\textsuperscript{3}, Y. Y. Yeoh\textsuperscript{1}, K. H. Yeo\textsuperscript{3}, D.-W. Kim\textsuperscript{3}, Jeong-Soop Lee\textsuperscript{1,4}, Dae M. Kim\textsuperscript{2} and Yoon-Ha Jeong\textsuperscript{1,4}

\textsuperscript{1}Pohang University of Science and Technology (POSTECH), Dept. of Electronic and Electrical Eng., Gyeongbuk, Pohang 790-784, Republic of Korea
Phone: +82-54-279-2897, E-mail: rock8201@postech.ac.kr
\textsuperscript{2}Korea Institute for Advanced Study (KIAS), School of Computational Sciences, Seoul 130-722, Republic of Korea
\textsuperscript{3}Samsung Electronics Company, Semiconductor R&D Center, Gyeonggi, Yongin 449-711, Republic of Korea
\textsuperscript{4}National Center for Nanomaterials and Technology (NCNT), Gyeongbuk, Pohang 790-784, Republic of Korea

1. Introduction
The gate-to-channel capacitor provides the fundamental device information such as EOT (electrical oxide thickness), flat band voltage, inversion charge, mobility, etc. and is useful for evaluating the device performance and characteristics [1-2]. However, as the active area (WxL) decrease, the capacitance of single device becomes small and hard to measure. Also, the gate tunneling current with thin oxide distorts the C-V shape [3-4]. Fortunately, the nanowire FET shows low gate leakage due to gate-all-around structure [5] but still suffers from the extremely small active area problem.

In this paper, we report the C-V characteristics measured from nanowire capacitor (NWCAP), which has been fabricated by connecting in parallel a number of identically processed nanowire FETs. Various capacitances were measured by using different electrode configurations. Moreover, we analyzed the effect of undoped and floating channel on the C-V curves and extracted accurate inversion charge ($Q_{\text{inv}}$) and mobility. The measured data were compared extensively with conventional planar MOSFETs. Various capacitances were measured by using different active area for accurate comparison.

2. GAA nanowire FET array structure and measurements
Fig. 1 shows a 4-port single nanowire FET structure. Because the device was fabricated on bulk silicon, the nanowire FET has a bottom Si and it is connected with Body contact. The undoped channel was surrounded by Gate and it thus floats on the bottom Si. The oxide was formed by in-situ steam generated (ISSG) process with $T_{\text{ox}}=3.3$ nm. The NWCAP has 100 by 100 array with Si. The oxide was formed by in-situ steam generated (ISSG) capacitor (MOSCAP) data.

3. Frequency response of undoped floating channel
For investigating the undoped floating channel effect, we measured the various capacitance components ($C_{\text{gd}}$, $C_{\text{gs}}$, $C_{\text{gd}}$) per unit area from both NW- and MOSCAP and have presented the data in Fig. 2-5. All capacitance values were normalized by active area for accurate comparison.

4. Results and Discussions
Fig. 6 shows the inversion capacitance per unit area $C_{\text{inv}}$, which is obtained by rejecting overlap capacitance ($C_{\text{ov}}=9.1$ F/\text{um} in NWCAP, 0.42 F/\text{um} in MOSCAP) from the $C_{\text{gd}}$ at 1MHz with $V_{\text{gs}}=-3$ V and -2V, respectively. As shown in Fig. 6, the NWCAP has larger $C_{\text{inv}}$ than MOSCAP in spite of the thicker oxide used and shows excellent gate controllability for channel inversion, as expected. $Q_{\text{inv}}$ shows its corresponding inversion charge per unit area.

Using the extracted $Q_{\text{inv}}$, $R_{\text{sd}}$ [6] and $L_{\text{sd}}$, we obtained the accurate mobility from the single FET via the well known eq. (1) and presented the $\mu$-$V_{\text{gs}}$ curves in Fig. 7. Although larger $Q_{\text{inv}}$ was attained in the NWCAP, the extracted mobility therein is smaller than MOSCAP's. It indicates that the carrier transport in nanowire limited by lateral factors e.g. series resistance, potential barriers at Source/Drain, etc., and not by vertical factors. However, if the mobility is calculated by using channel diameter of 12 nm in [7], its values are comparable with planar MOSFET.

4. Conclusions
In this study, we have investigated the gate response of undoped
and floating channel by measuring various C-V data from nanowire capacitor arrays. The undoped channel in nanowire suffers from slower frequency response but it is not a serious problem in inversion region in which device operates. In addition, the NWCAP is shown to exhibit superior channel inversion with higher \( Q_{inv} \), compared with the planar MOSCAP. Thus, the performance of nanowire FET could be greatly improved with the process refinements made in Source/Drain contacts. Also, the overlap capacitance has to be reduced for high frequency applications.

**Acknowledgements**

This research was supported by World Class University (WCU) program through the Korea Science and Engineering Foundation funded by the Ministry of Education, Science and Technology. (Project No. R31-2008-000-10100-0). Also, this work was supported by National Research Foundation of Korea Grant funded by the Korean Government (2009-0089200) and partially supported by the BK21 program, the National Center for Nanomaterials Technology (NCNT) in Korea and "System IC 2010" project of Korea Ministry of Knowledge Economy. Finally, the authors thank Samsung Electronics Co., Ltd. for device fabrication.

**References**


![Fig.1. Cross-sectional diagram of 4-port single nanowire FET.](image1)

![Fig.2. C\(_{gsd}^\prime\) comparison with different frequency between NW- and MOSCAP. There is no capacitance distortion in NWCAP.](image2)

![Fig.3. C\(_{inv}\) comparison with different frequency between NW- and MOSCAP. To observe the body effect only, the Body were opened.](image3)

![Fig.4. C\(_{gsd}^\prime\) comparison with different frequency between NW- and MOSCAP. To observe the S/D effect only, the Body was opened.](image4)

![Fig.5. C\(_{gsd}^\prime\), C\(_{gd}^\prime\), C\(_{gb}^\prime\), C\(_{gd}^\prime\) and C\(_{gb}^\prime\) variation versus \( V_g \) at 500 kHz.](image5)

![Fig.6. C\(_{inv}\) and \( Q_{inv}\) comparison between NW- and MOSCAP. The NWCAP shows excellent electrostatic properties in spite of thicker T\(_{ox}\).](image6)

![Fig.7. Comparison of mobility between nanowire and planar FET within similar channel lengths.](image7)

\[
\mu = G_{ch} \times \frac{L_{eff}^2}{Q_{inv}}
\]

### Table 1. Capacitance components of NWCAP

<table>
<thead>
<tr>
<th>C(_{gsd}^\prime)</th>
<th>Accumulation</th>
<th>Inversion</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(_{gd}^\prime)</td>
<td>Fast ( h^\prime ) C/D from Body (Region II in Fig.1)</td>
<td>Fast ( e^\prime ) C/D from Source/Drain and some slow ( e^\prime ) from Body (Region I, II in Fig.1)</td>
<td>-</td>
</tr>
<tr>
<td>C(_{gb}^\prime)</td>
<td>Fast ( h^\prime ) C/D from Body (Region II in Fig.1)</td>
<td>Slow ( e^\prime h^\prime ) generation from Body (Region II in Fig.1)</td>
<td>S/D floating</td>
</tr>
<tr>
<td>C(_{gsd}^\prime)</td>
<td>Slow ( e^\prime h^\prime ) generation in channel (Region I in Fig.1)</td>
<td>Fast ( e^\prime ) C/D from the Source/Drain (Region I in Fig.1)</td>
<td>Body floating</td>
</tr>
</tbody>
</table>

\* C/D(charging/discharging), \( h^\prime \) (hole), \( e^\prime \) (electron)