Speed Enhancement at $V_{dd} = 0.4$ V and Random $\tau_{pd}$ Variability Reduction of Silicon on Thin Buried Oxide (SOTB)

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Abstract - Ring oscillator characteristics of silicon on thin buried oxide (SOTB) were investigated at $V_{dd}$ down to 0.4 V. It was demonstrated that both the propagation delay ($\tau_{pd}$) and energy-delay (ED) product of SOTB are smaller than those of bulk devices due to its steeper subthreshold swing. It was found that the $\tau_{pd}$ variability of SOTB is dominated by global variability because of small local variability due to the intrinsic channel. The $\tau_{pd}$ variability is mainly determined by the global drive-current variability and thus can be easily reduced by die-to-die substrate bias voltage control.

I. INTRODUCTION

The silicon on thin buried oxide (SOTB) [1] is a strong candidate for ultralow-voltage operation of CMOS due to small threshold-voltage ($V_{th}$) variability and back-bias control [2]. Advantages of SOTB device characteristics for supply voltage ($V_{dd}$) reduction have been reported [3-5]. To achieve the ultralow-power LSI, demonstration of stable circuit operation at low $V_{dd}$ is necessary. However, increasing delay variability at low $V_{dd}$ is an important challenge. In this paper, propagation delay variability of SOTB at $V_{dd}$ down to 0.4 V was investigated through ring oscillator (RO) measurements.

II. FABRICATION AND MEASUREMENT

RO circuits were fabricated by 65 nm SOTB process [5,6] on silicon on insulator (SOI) substrate of 10-nm thick buried oxide (BOX) (Fig. 1). Bulk ROs of the same $V_{th}$ as SOTB at $V_{dd} = 0.4$ V were fabricated as controls. The propagation delay time ($\tau_{pd}$) was evaluated through measurements of many chips in a whole wafer. The dc characteristics of specific transistors were also measured to analyze delay characteristics.

III. RESULTS AND DISCUSSION

A. Propagation delay and ED product

Figure 2 shows $V_{th}$ shift with varying $V_{dd}$. $V_{th}$ shift of SOTB is obviously smaller than that of bulk due to small drain induced barrier lowering (DIBL). The $\tau_{pd}$ of SOTB is smaller than that of bulk at $V_{dd} = 0.4$ V, at the same $V_{th}$ (Fig. 3). Furthermore, SOTB has smaller $\tau_{pd}$ than bulk in a whole range of $V_{dd}$ in spite of higher $V_{th}$ than bulk at $V_{dd} > 0.4$ V. It is because SOTB has higher effective drive current ($I_{eff}$) [7] than bulk at the same $I_{eff}$ due to steeper sub threshold swing characteristic (Fig. 4). This feature of SOTB enhances operation speed especially at low $V_{dd}$. As a result, energy-delay (ED) products [8] of SOTB is superior to those of bulk (Fig. 5). Note that $V_{min}$ of the ED product for SOTB decreases down to 0.5 V with decreasing the $V_{th}$ down to 0.15 V (not shown).

Small $\tau_{pd}$ and ED of SOTB is demonstrated for a wide range of $V_{dd}$.

B. Delay variability

ROs with various numbers of stages were measured to examine $\tau_{pd}$ variability ($\sigma_{\tau_{pd}}$) at $V_{dd} = 0.4$ V. The $\sigma_{\tau_{pd}}$ should be proportional to $1/\sqrt{N}$ ($N$: number of stages) if it is caused by local variability [9,10]. Figure 6 shows $1/\sqrt{N}$ dependence of $\sigma_{\tau_{pd}}$. The $\sigma_{\tau_{pd}}$ of bulk increases proportional to $1/\sqrt{N}$. By contrast, the $\sigma_{\tau_{pd}}$ of SOTB is almost constant. This result indicates the $\sigma_{\tau_{pd}}$ of SOTB is not affected by the local variability.

To investigate the origin of $\sigma_{\tau_{pd}}$ of 101- and 25-stage ROs in a whole wafer were plotted (Fig. 7). There is a strong correlation between them only for SOTB. This means that the $\sigma_{\tau_{pd}}$ of SOTB shows the systematic behavior. Then, $\sigma_{\tau_{pd}}$ is calculated (Fig. 8) by taking two factors, global and local terms, $\sigma_{\tau_{pd,global}}$ and $\sigma_{\tau_{pd,local}}$, respectively, into account. The $\sigma_{\tau_{pd,global}}$ is assumed to be constant and the $\sigma_{\tau_{pd,local}}$ is estimated from the experimental local $V_{th}$ variability data [4]. The $\sigma_{\tau_{pd,local}}$ of bulk is proportional to $1/\sqrt{N}$ due to large $\sigma_{\tau_{pd,local}}$. On the other hand, in SOTB, $\sigma_{\tau_{pd,local}}$ shows weak dependence with $1/\sqrt{N}$. The calculation clearly reproduced the measurement results. We thus concluded that the $\sigma_{\tau_{pd}}$ of SOTB is dominated by the $\sigma_{\tau_{pd,global}}$ because of the small $\sigma_{\tau_{pd,local}}$ with the intrinsic channel.

If $\sigma_{\tau_{pd}}$ is caused by the systematic variability of $V_{th}$, it can be easily controlled by back biasing [1,5]. The relation between $\tau_{pd}$ and $1/I_{eff}$ is shown in Fig. 9. The $\tau_{pd}$ of SOTB strongly correlate with $1/I_{eff}$. This means the $\sigma_{\tau_{pd}}$ of SOTB is mainly caused by the global $I_{eff}$ variability. On the other hand, in bulk, there is a weak correlation between $\tau_{pd}$ and $1/I_{eff}$ suggesting that the $\sigma_{\tau_{pd}}$ is mainly determined by the local variability of $V_{th}$ caused by RDF. In SOTB, we can easily reduce $\sigma_{\tau_{pd}}$ by correcting $V_{th}$ by changing die-to-die substrate voltage.

IV. CONCLUSION

The propagation delay ($\tau_{pd}$) and $\tau_{pd}$ variability ($\sigma_{\tau_{pd}}$) of SOTB ring oscillator were investigated. SOTB has smaller $\tau_{pd}$ and ED product than those of bulk under a wide range of supply voltage down to 0.4 V. It is revealed that $\sigma_{\tau_{pd}}$ of SOTB is dominated by die-to-die global variability due to its small local variability. Therefore, the delay variability of SOTB can be significantly reduced by back-bias control. This feature is a significant advantage of SOTB for the ultralow-voltage operation of LSI.
operation of CMOS.

ACKNOWLEDGMENT

This work was performed as “Ultra-Low Voltage Device Project” funded and supported by METI and NEDO, Japan.

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