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Speed Enhancement at V_{dd} = 0.4 V and Randam τ_{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 (τ_{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 τ_{pd} variability of SOTB is dominated by global variability because of small local variability due to the intrinsic channel. The τ_{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 (τ_{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 τ_{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 τ_{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_{off} 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 τ_{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 τ_{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 $\sigma_{\tau pd}$, τ_{pd}s 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 $\sigma_{\tau pd,global}$ was assumed to be constant and the $\sigma_{\tau pd,local}$ is estimated from the experimental local V_{th} variability data [4]. The $\sigma_{\tau pd}$ of bulk is proportional to $1/\sqrt{N}$ due to large $\sigma_{\tau pd,local}$. On the other hand, in SOTB, $\sigma_{\tau pd}$ 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 τ_{pd} and $1/I_{eff}$ is shown in Fig. 9. The τ_{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 τ_{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 (τ_{pd}) and τ_{pd} variability ($\sigma_{\tau pd}$) of SOTB ring oscillator were investigated. SOTB has smaller τ_{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 CMOS.

ACKNOWLEDGMENT

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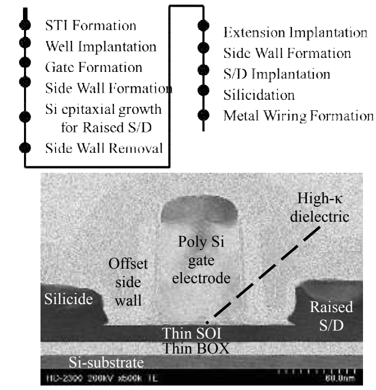

Fig. 1 Fabrication process and TEM image of SOTB transistor.

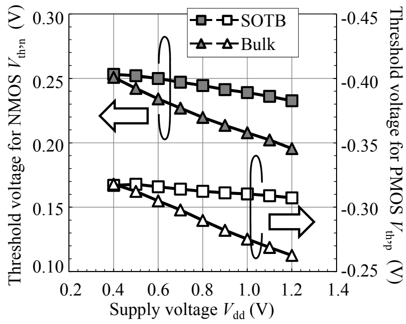

Fig. 2 Supply voltage (V_{dd}) dependence of threshold voltage (V_{th}).

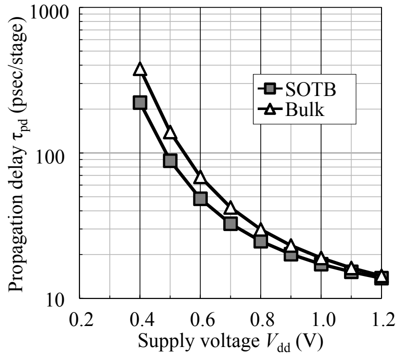

Fig. 3 Supply voltage (V_{dd}) dependence of propagation delay time.

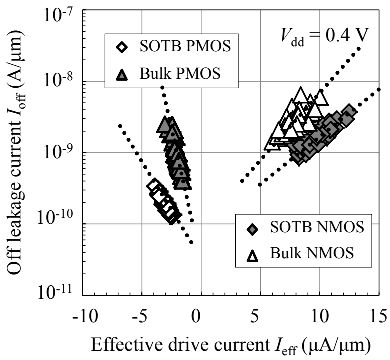

Fig. 4 I_{eff}-I_{off} characteristics for SOTB and bulk. SOTB has higher I_{eff} than bulk at the same I_{off}.

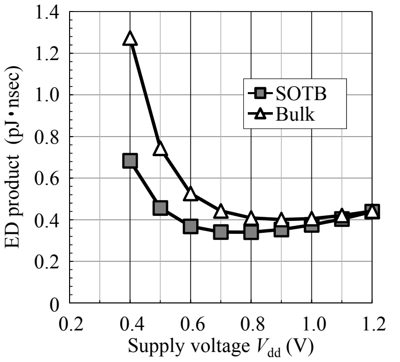

Fig. 5 Supply voltage (V_{dd}) dependence of energy-delay product of 101 stage RO. Energy is defined by $I_{dd}V_{dd}$ / frequency. I_{dd} is active current of RO.

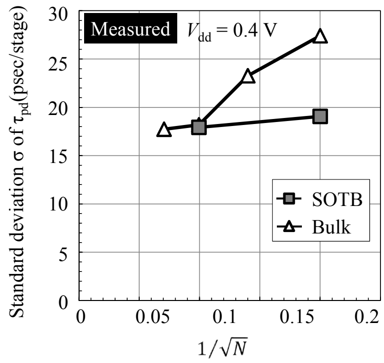

Fig. 6 Measured $1/\sqrt{N}$ dependence of standard deviation of propagation delay time ($\sigma_{\tau pd}$).

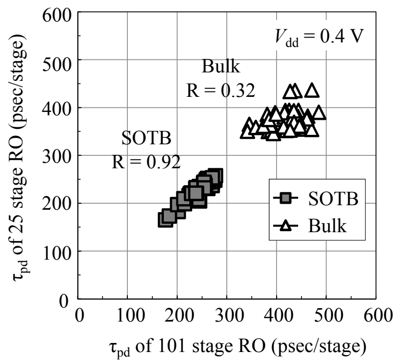

Fig. 7 Correlation between delays of 101- and 25-stage ROs. The correlation coefficients are R = 0.92 and 0.32 for SOTB (■) and bulk (∆), respectively.

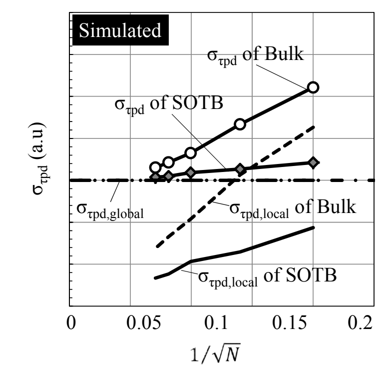

Fig. 8 Simulated $\sigma_{\tau pd}$ - $1/\sqrt{N}$ relationship. $\sigma_{\tau pd,local}$ and $\sigma_{\tau pd,global}$ denote local and global variability, respectively. $\sigma_{\tau pd}$ is defined by root sum square of $\sigma_{\tau pd,local}$ and $\sigma_{\tau pd,global}$.

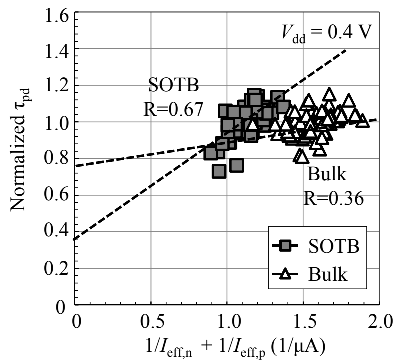

Fig. 9 Relation between normalized τ_{pd} (τ_{pd}/median) and 1/ $I_{eff,n}$ +1/ $I_{eff,p}$. $I_{eff,n}$ and $I_{eff,p}$ denote effective drive currents of N and PMOS, respectively.