0.5-V 50-mV-Swing 1.2-GHz 28-nm-FD-SOI 32-bit Dynamic Bus Architecture with Dummy Bus

Khaja Ahmad Shaik, Kiyoo Itoh, Amara Amara

► To cite this version:

Khaja Ahmad Shaik, Kiyoo Itoh, Amara Amara. 0.5-V 50-mV-Swing 1.2-GHz 28-nm-FD-SOI 32-bit Dynamic Bus Architecture with Dummy Bus. ISQED, Mar 2016, Santa Clara, United States. hal-01254227

HAL Id: hal-01254227

<https://hal.science/hal-01254227>

Submitted on 11 Jan 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

0.5-V 50-mV-Swing 1.2-GHz 28-nm-FD-SOI 32-bit Dynamic Bus Architecture with Dummy Bus

Khaja Ahmad Shaik, Kiyoo Itoh, and Amara Amara

Institut supérieur d'électronique de Paris (ISEP), 10 Rue Vanves, Issy-les-Moulineaux, France. kshaik@isep.fr

Abstract—To achieve a 0.5-V low-power high-speed robust bus, a dynamic bus architecture, combined with a dynamic driver and a dynamic receiver for small leakage current with stacked MOSFETs, is proposed. In particular, the dynamic driver enables high speed even at 0.5 V with increased gate-over-drive by changing the power lines from $V_{DD}/2$ in the standby mode to V_{DD} in the active mode. It further speeds up with the help of another proposal of a dummy bus for tracking the bus-voltage detecting point for reducing the bus swing. Robustness of each proposal is investigated by Monte Carlo simulation. Then, a 0.5-V 28-nm-FD-SOI 32-bit bus architecture using the proposals is evaluated by simulation. The power-supply bounce noise and the reduction are also investigated here through the layout. As a result, it turns out that the architecture has a potential of operating a 1-pF bus at a 50-mV swing, 1.2 GHz, and a standby current of 1.1 μ A, with x3-5 faster and more than two-order lower standby current than the conventional static architecture.

Keywords—0.5-V 50-mV-swing dynamic bus, stacked MOSFETs, dummy bus, 32-bit dynamic bus architecture

1. Introduction

Low-power bus architectures for intra- and inter-chip communication have been strongly needed to cope with the ever-increasing interconnect power dissipation caused by larger interconnect capacitances [1]. Indeed, data-bus lines, address lines, control lines, and precharge lines running across a chip inevitably increase the capacitances with larger scale integration of chips. In addition, the number of the lines, especially for data buses in RAMs and MPUs, increases with the ever-stronger need for higher throughput, exemplified by as large as 1024 [2] for 3D integration such as Through-Silicon-Via (TSV)-3D chips. Such buses will continue to be indispensable even with power-supply (V_{DD}) and device scaling, calling for new circuits as well as low-capacitance interconnect technology. The most effective way is to lower the voltage swing on the bus. In line with this, many attempts have been made so far despite some drawbacks (such as limited reduction of the swing, and complicated and large area) being involved. Good examples are a flip-flop receiver [3], current-mode signaling [4], and differential buses [5]. Of these, N.C. Svensson's static bus architecture [6] is simple and most promising with respect to low-voltage-swing capability thanks to an inverter-amplifier in a receiver. Even so, the basic characteristics and design issues remain unknown, although optimization of the power dissipation was investigated. The

most serious issue of the attempts, however, is the fact that they were evaluated at V_{DD} higher than 1 V and with device feature sizes larger than 0.13 μ m. Obviously, considering that the state-of-the-art V_{DD} and devices for SoCs are 0.6 V and 14 nm even at the commercial base [7], the bus architectures must keep up with the scaling because they will be eventually embedded in such SoCs. Hence, the ever-increasing subthreshold leakage (off) current with reducing V_t and degraded robustness by V_t -variations with device scaling [8] are emerging issues for the bus design. Well-known stacked-MOSFETs for low-leakage current are thus indispensable. Moreover, the use of fully-depleted SOI MOSFETs [9] is vital for smaller V_t -variations. Note that using bulk MOSFETs may be intolerable, considering the standard deviation (σV_t) of the local V_t -variation [8] given as $\sigma V_t = A_{vt}/(LW)^{1/2}(A_{vt}$; the Pelgrom coefficient). This is because the necessary channel width W s are expected to be almost quadrupled for a given σV_t . Here, as for the global V_t -variation, which influences speed, the so-called back plain control by detecting the average V_t [10] is effective. In addition to the above scaling issues, to the best of our knowledge, multi-bit bus architectures, indispensable for data bus in DRAMs and embedded SRAMs in SoCs, remain unreported.

In this paper, first, design issues of Svensson's conventional static bus (S-BUS) with the inverter-amplifier are clarified. Then, a dynamic bus architecture (D-BUS) to cope with the issues is proposed. It consists of a dynamic driver, a dynamic receiver, and a dummy bus for smaller bus swing for high speed and low power. Some of them are then evaluated in terms of speed and robustness by Monte Carlo simulation. Noise issue is also briefly discussed. Finally, a 32-bit bus architecture using the proposals and 28-nm FD-SOI MOSFETs is evaluated by simulation and the layout.

2. Design Issues of Conventional Static Bus

Fig. 1 shows the conventional S-BUS [6]. The bus consists of a gate-source offset-driven CMOS inverter [3] for a driver (DRV), and amplifiers with symmetric CMOS inverters (i.e., with $W_p/W_n \cong 2.5$) for a receiver (REC), each trip point of which is set to $V_{DD}/2$ for maximizing the amplification. DRV operates at power supplies of $(V_{DD}/2 + V_s)$ and $(V_{DD}/2 - V_s)$, so the bus is biased at $V_{DD}/2$ and swings at signal components $\pm V_s$ that corresponds to the input IN data "1"(H) or "0"(L). The first inverter IV_1 amplifies and discriminates $\pm V_s$, referring to $V_{DD}/2$. For example, at $V_s = 50$ mV, a signal component +50 mV superposed on the $V_{DD}/2$ (point **m**) is amplified and a low enough voltage (point **l**) is thus outputted at OUT_1 . In contrast,

Fig. 4 (a) V_{offmax} and (b) BUS-driving speeds for $W(M_{nd})$.

$V_{off}(DRV)$ vs. $W(M_{nd})$ when the V_t -variation is taken into account by Monte Carlo simulation with 1,000 samples. Here, $W(M_{pd})$ was trimmed whenever $W(M_{nd})$ was changed, so DRV became always symmetric. Other W -ratios to $W(M_{nd})$, however, are constant, namely, $W(M_d)/W(M_{nd}) = 1.25$, $W(M_s)/W(M_{nd}) = 0.5$, $W(M_{l-M_2})/W(M_{nd}) = 0.2$, and $W(M_a)/W(M_{nd}) = 2$ for D-DRV, while $W(M_{pd})/W(M_{nd}) \cong 2$ for S-DRV. Obviously, V_{off} s decrease with increasing the W , as expected from the above-mentioned expression on σV_t . Although D-DRV has larger $V_{off}(DRV)$ due to additional small M_d and M_s , the drawback is offset by larger GOD. Indeed, as seen in Fig. 4(b), the signal developing time t_r , the precharge time t_f , and thus t_{cmin} , defined at $V_s = 50$ mV and $V_n = 5$ mV (noise) for “0” input, as in Figs. 3(c) and (d), are shorter with more reduced variation than those of S-DRV. Fig. 5 shows the signal characteristics. Obviously, t_r becomes longer with increasing V_s , as mentioned before, calling for reduction of the necessary V_s for fast cycle. The reduction strongly influences the cycle time, since BUS is slowly driven due to a large C_B . As for t_f , it becomes longer with V_n for a given V_s of 50 mV, due to need for longer precharging time. Here, V_n works as noise for the next cycle with the incomplete precharging voltage. Thus, faster BUS-precharging is necessary for faster cycle with the help of the accelerator ACC.

Here, let's investigate the robustness of a BUS with $W(M_{nd}) = 10 \times 80$ nm, when a 841-ps-cycle pulse (P) with an active pulse width t_w of 353 ps and an off-pulse width t_{off} of 488 ps is provided by the dummy bus (DM-BSA), as discussed later. Since t_w and t_{off} are almost equal to the BUS-driving speed t_r and precharging speed t_f , respectively, the BUS generates a V_s of 37 mV and a V_n less than 5 mV, as seen in Fig. 5. Hence, if the total noise including other noise components is less than 32 mV ($= 37 - 5$), the BUS-stability is ensured.

Fig. 5 Signal characteristics of D-DRV. Fig. 6 (a) Stacked-MOSFET-inverters in REC and symbols, (b) transfer curves of IV_1 .

Fig. 7 (a) V_{OUT1} and V_{off} converted to BUS, and (b) V_{BUS} vs. V_{OUT1} for $W(M_n)$. M_n ; nMOSFET in IV_1 .

B. Dynamic Receiver (D-REC)

It uses the same circuit and LVT MOSFETs as S-BUS, except for the dynamic operation. Major concerns here are the large DC current and the offset voltage $V_{off}(REC)$ of IV_1 , both of which are not imposed on the succeeding stages due to amplified gate-voltages. The current is reduced by a dynamically-operated stacked-MOSFET (e.g., M_{nst} in Fig. 6(a)). In this circuit, while the pulse P is at 0.5 V at the first half of cycle, M_{nst} turns on for active operation with a quite large current due to operating at about $V_{DD}/2$. At the second half of cycle with P at 0 V (precharge period), the current is reduced to a negligible level (e.g., from $8\mu A$ to 31 nA, see Fig. 8(c)) that is equal to a small subthreshold current of M_{nst} . Hence, the current is almost halved in the active mode at a 50% duty cycle, while negligible in the standby mode. The more detail will be discussed later. As for $V_{off}(REC)$, Fig. 7 depicts the IV_1 -output and variations vs. $W(M_n)$, taken by Monte Carlo simulation. $V_{off}(REC)$ is the deviation from $V_{DD}/2$, as mentioned previously. For example, for $W(M_n) = W(M_{nst}) = 10 \times 80$ nm, V_{out1} ranges from 425 mV to 93 mV (see Fig. 7(a)). They correspond to 225 mV and 270 mV if converted to the input (i.e., BUS) (see Fig. 7(b)), implying that $V_{off}(REC)$ s are 25 mV and +20 mV, respectively. Since $V_{off}(REC)$ is the

Fig. 8 Optimum sets of W s for (a) D-BUS, and (b) S-BUS, and (c) leakage current of each stage for the optimum set. Numeral denotes $W(x80$ nm) for DRV, while $W(x80$ nm) for nMOSFET in REC.

effective noise on BUS that decreases with increasing $W(M_n)$, the noise is 25 mV for $W(M_n) = 10 \times 80$ nm. Based on the results, optimum sets of W s for D-BUS and S-BUS are exemplified in Figs. 8(a) and (b). Leakage currents for inputs “0” and “1” of each stage for the sets are shown in Fig. 8(c). In the active mode, the total current is almost dominated by IV_1 -current that is as large as 12 μ A and 8 μ A for S-BUS and D-BUS with P at 0.5 V, respectively. In the standby mode, however, IV_1 -current is drastically reduced to 31 nA with P at 0 V for D-BUS, while it remains to 12 μ A for S-BUS. Note that the active current of D-BUS is almost halved to 4 μ A for a duty cycle of 50%.

C. Dummy BUS (DM-BSA)

Dummy bus eventually governs performances of the whole architecture explained later, since the above-described bus operates under the control of dummy bus. Fig. 9 shows a proposed dummy bus architecture (DM-BSA) composed of a pulse generator PGR, a dummy driver DRV_D , a dummy bus BUS_D , a dummy receiver REC_D , another dummy receiver REC_D at the near end, and a delay (τ). All the circuit blocks, except for PGR, use almost the same circuit configuration, structure, size, and layout, as the above-described D-BUS. Hence, two signal detecting points, corresponding to $\pm V_s$, of the IV_1 in the above-described D-REC are automatically tracked by the pulse from PGR even under variations of fabrication process, voltage including power-supply bounces, and temperature. As for PGR, triggered by a global precharge pulse P_G and controlled by BUS_D , REC_D at the near end, and the delay, it self-generates pulses for driving D-BUS. The ACC, however, is deleted due to no need for the operation. During long standby periods, P_G turns off to make all the dummy bus and buses at a low leakage mode with the stacked MOSFETs off, benefitting hand-held equipment. Just after P_G goes up to 0.5 V, normal operations start. Hence, a NAND in PGR starts generating local pulses P_N and P_F with always turning on all the inverters in REC_D (thus static operations with P_G at 0.5 V), while performing dynamic operations for

the inverters in D-BUS. Note that P_N and P_F correspond to P in the previous figures (e.g., Fig. 2). Separated REC_D s at the near end and the far end make the design of the architecture simple and robust, enabling to cancel the bus delay effect. Hence, the one at the near end can generate pulse P_N to control DRV s at the near end (see Fig. 11), independently of the other REC_D controlled by pulse P_F at the far end. Even for the dummy bus, noise on BUS_D must be reduced since it determines the necessary V_s on BUS_D . If power-supply noise is negligible with noise reduction techniques described later, the tolerable total noise on BUS_D is 25 mV, equal to $V_{off}(REC)$, since ACC is deleted.

A level shifter LSFT generates pulses P_{N1} and $/P_{N1}$ to drive D- DRV s in Fig. 2. It features using gate-source differentially-driven ZVT-MOSFETs for quickly shifting a 0.5-V P_N to V_{pp} ($= 1$ V) pulse P_{N1} . Tapered- W inverters [11] are used to drive a large capacitance coming from 32-buses with small area and low power. V_{pp} can be generated with a well-known on-chip voltage doubler. Fig. 9(c) illustrates simulated waveforms. BUS_D builds up from V_{ss} after P_G -activation and starts to oscillate at a cycle t_c of 0.84 ns and a V_s of ± 25 -30 mV that is smaller than the above-described noise. From the waveforms, the bus delay is about 0.42 ns, which is the same as that for D-BUS due to the same circuit. The V_s and cycle time t_c of dummy bus are adjustable with $W(M_{nd})$ in DRV_D and a delay (τ), respectively, as shown in Fig. 10.

Fig. 10 Characteristics of dummy bus (a) without delay, and (b) with delay (τ); t_c , cycle time, $\pm V_s$; signal swing on dummy bus.

4. Application to 32-bit Buses

A. Architecture and Performances

Fig. 11 shows a 32-bit D-BUS architecture, in which optimum parameters in Fig. 8 for D-BUS and Fig. 9 for dummy bus (DM-BSA) are used to ensure high speed and stable operations. Taper CMOS buffers [11], BF_1 and BF_2 in DM-BSA, and buffers BF_0 s in each REC enable to reduce the load capacitance of REC_D and the P_F -capacitance that is usually large because one dummy bus commonly controls 32 buses. Fig. 12 illustrates simulated waveforms. A 1-pF BUS operates successfully at 0.5-V 0.84-ns cycle (1.2 GHz), as expected, and as mentioned in detail below. Note that if the signal discrimination levels for “1” and “0” are $V_{DD}/2$ ($= 0.25$ V), an input pattern of “0” “1” “0” “1” starts to be discriminated at point S at each cycle. In addition, since the output (OUT_0) becomes invalid at point T when it starts to be

Fig. 9 (a) Dummy bus architecture (DM-BSA), and (b) level shifter (LSFT), and (c) waveforms using W s optimized for D- DRV and D- REC .

Fig. 11 32-bit bus architecture using D-BUS and DM-BSA. BF_0 is in Fig. 9.

Fig. 12 Waveforms of the 32-bit architecture.

precharged to 0.5 V by $/PF_1$. Therefore, OUT_0 is valid between S and T at each cycle. Despite spurious outputs due to incomplete BUS-precharging and a high gain of IV_1 , the input pattern is successfully transmitted to OUT_0 , as seen in the figure. Obviously, V_s is 30-40 mV on BUS_0 , which are larger than the assumed noise ($= 25 + 5 = 30$ mV), thus ensuring stable operations. Such high-speed and stable operations, however, are never realized without reducing the following power-supply-noise in the architecture.

B. Noise Reduction

Fig. 13 shows noise sources, related to power-supply fluctuations in D-BUS, and the reductions. For example, to reduce an inaccurate $V_{DD}/2$ DC-level from an on-chip generator (HVG), laser trimming of the poly-Si resistors, well established for memory repair [12], is effective. A transient fluctuation may occur at the $V_{DD}/2$ line due to shortage of the driving capability of HVG, when P_N (i.e., P in Figs. 2 and 8(a)) inputted to ACC drives a large BUS capacitance. However, it may quickly recover if HVG enables to detect the fluctuation, followed by feedback for stabilization [13]. Ideally, the $(V_{DD} + V_{SS})/2$ level of each PSC, ACC, and REC must be always equal statically and dynamically to the $V_{DD}/2$

Fig. 13 (a) Noise sources, and (b) shielded BUS with V_{DD} and V_{SS} lines. HVG; $V_{DD}/2$ -generator [13].

level from HVG. Otherwise the difference works as noise, thus calling for a tight and close layout of relevant circuits with wide-enough power lines. This is also the case for each V_{DD} line and each V_{SS} line. In general, however, it is usually difficult to reduce the V_{DD} - and/or V_{SS} -level difference between the near end (e.g., PSC) and far end (e.g., D-REC) due to small parasitic resistances (r_{ps}) between them. In addition, there exists line-to-line BUS coupling. A bus-line shielding scheme proposed in Fig. 13(b) may reduce not only the level difference with effectively wide enough power lines, but also the line-coupling. Fig. 14 illustrates the layout of the 32-bit architecture incorporating the shielding scheme. The BUS-M3-metal line pitch is 600 nm with a width of 100 nm for BUS and power lines and a space of 200 nm. A bus capacitance of 1 pF comes from a bus line of about 20 mm long. Area overhead by D-BUS is only 6.7% for a given BUS pitch.

Fig. 14 Layout of 32-bit bus architecture with optimum parameters in Figs. 8 and 9.

		Proposed(D-BUS)	Conv. (S-BUS)	Remarks
$V_t(M_{nd})$		LVT(254 mV)	LVT	Fig.8
$W(M_{nd})/W(M_n)$		10/10x80 nm	40/10x80 nm	Fig.8
BUS swing ($\pm V_s$)		± 50 mV	± 50 mV	
Typ. speed (ratio)	Delay	$\cong 0.42$ ns (0.17)	$\cong 2.5$ ns (1)	$C_b=1$ pF, Fig.9
	Cycle time	0.84 ns (0.34)	$\cong 2.5$ ns (1)	$C_b=1$ pF, Fig.9
Leakage current	Active	144 μ A	384 μ A	Fig.8, duty 50%
	DM-BSA	16 μ A	–	
	Standby	1.1 μ A	384 μ A	Fig.8, P_G 0 V
DM-BSA		62 nA	–	
Area overhead		6.7%	0	Fig.13
On-chip converters		0.25 V, 1 V	0.2 V, 0.3 V	

Fig. 15 Performances of 0.5-V 32-bit D-BUS architecture, compared with the conventional.

C. Summary

Fig. 15 compares performances between the proposed 32-b D-BUS and the conventional 32-b S-BUS, assuming that power-supply noise becomes negligible with noise-reduction techniques. Note that the D-BUS realizes a short delay of about 0.42 ns and a fast cycle time of 0.84 ns (1.2 GHz) with x3-5 faster than the S-BUS. For a more realistic bus length of 1cm, the cycle is doubled to 2.2 GHz. In addition, the total DC current in the active mode, dominated by IV_1 -current, is 144 μ A for D-BUS and 384 μ A for S-BUS. The current in the standby mode is 1.1 μ A only for D-BUD while 384 μ A for S-BUS, with more than two-order reduction with D-BUS.

5. Conclusion

To achieve a 0.5-V low-power high-speed robust bus, a dynamic bus architecture, combined with a dynamic driver and a dynamic receiver for small leakage current with stacked MOSFETs, was proposed. In particular, the dynamic driver enables high speed even at 0.5 V with increased gate-over-drive by changing the power lines from $V_{DD}/2$ in the standby mode to V_{DD} in the active mode. It further speeds up with the help of another proposal of a dummy bus for tracking the bus-voltage detecting points for reducing the bus swing. Robustness of each proposal was investigated by Monte Carlo simulation. Then, a 0.5-V 28-nm-FD-SOI 32-bit bus architecture using the proposals was evaluated by simulation. The power-supply bounce noise and the reduction were also investigated through the layout. As a result, it turned out that the architecture has a potential of operating a 1-pF bus at a 50-mV swing, 1.2 GHz, and a standby current of 1.1 μ A, with x3-5 faster and more than two-order lower standby current than the conventional static architecture.

Acknowledgement

The authors thank Circuit Multi Projects (CMP), Grenoble, France for providing the FD-SOI 28nm design kit (DK), and STMicroelectronics, Crolles, France for the DK support.

References

- [1] D. Liu and C. Svensson, "Power consumption estimation in CMOS VLSI chips," IEEE J. Solid-Sate Circuits, vol. 29, pp.663-670, June 1994.
- [2] T. Sekiguchi, K. Ono, A. Kotabe, and Y. Yanagawa, "1-Tbyte/s 1-Gbit

- DRAM architecture using 3-D interconnect for high-throughput computing," IEEE J. Solid-State Circuits, vol. 46, no. 4, pp. 828-837, Apr. 2011.
- [3] Y. Nakagome, K. Itoh, M. Isoda, K. Takeuchi, and M. Aoki, "Sub-1-V swing internal bus architecture for future low-power ULSI's," IEEE J. Solid-State Circuits, vol. 28, pp. 414 -419, Apr. 1993.
- [4] A. Katoch, H. Veendrick, and E. Seevink, "High Speed Current-mode Signaling Circuits for On-Chip Interconnects," in Proc. IEEE Int. Symp. Circuits Syst., 2005, pp. 4138-4141.
- [5] H. Zhang, V. George, and J. M. Rabaey, "Low-Swing On-Chip Signaling Techniques: Effectiveness and Robustness," IEEE Trans. VLSI Systems, vol. 8, No.3, pp. 264-272, June 2000.
- [6] C. Svensson, "Optimum Voltage Swing on On-Chip and Off-Chip Interconnect," IEEE J. Solid-State Circuits, vol. 36, No.7, pp. 1108-1112, July 2001.
- [7] Eric Karl et al., "A 0.6V 1.5GHz 84Mb SRAM Design in 14nm FinFET CMOS Technology," ISSCC Dig. , pp. 310-311, Feb. 2015.
- [8] N. Sugii, "Low-power-consumption fully depleted silicon-on-insulator Technology," Microelectronic Engineering 132(2015)226-235.
- [9] P. Flatresse, et al., "Ultra Wide Body Bias Range LDPC decoder in 28nm UTBB FDSOI Technology", ISSCC Dig., pp. 424-425, Feb. 2013.
- [10] S. G. Narendra and A. Chandrakasan, *Leakage in Nanometer CMOS Technologies*, Springer, 2005.
- [11] S. R. Vemuru and A. R. Thorbjornsen, "Variable-Tapaer CMS Buffere," IEEE J. Solid-State Circuits, vol. 26, No.9, pp. 1265-1269, Sept. 1991.
- [12] K. Itoh, *VLSI Memory Chip Design*, Springer, 2001.
- [13] Y. Nakagome et al., "An Experimental 1.5-V 64-Mb DRAM," IEEE J. Solid-State Circuits, vol. 26, No.4, pp.465-471, April 1991.