Current-Controlled Switches for HV SoI Processes – Structure, Application and Integration in Functional Blocks

M. Jankowski, *Member, IEEE,* and A. Napieralski, *Senior Member, IEEE*

Department of Microelectronics and Computer Science, Lodz University of Technology
Wolczanska 221/223, 90-924 Lodz, Poland, jankowsk@dmcs.pl

ABSTRACT

The paper presents an approach to design of high-voltage current-controlled switches. HV switch structures, properties, application possibilities as well as ways of merging these switches into structure of HV signal-processing components, are discussed. New HV switch structures are specialized and modified for specific applications. The switches structures and modes of operation are introduces, simulated and discussed.

Keywords: high-voltage circuits, analog switches, current-mode control, current processing, voltage processing.

1 INTRODUCTION

This work is motivated by research related to HV SoI ASICs for automotive applications. Research activities conducted as a part of the chip design have shown that HV switches may turn out inevitable in signal paths. Though, there is an issue with switches – or transmission gates – for HV applications. It is based on different properties of LV and HV MOS devices. Usually, LV MOS transistors are (or can be) symmetrical structures having very similar maximum safe-voltage drops between any two terminals. In case of HV transistors maximum voltage limits usually are different. Many HV MOS devices have in fact their gate-source voltages limited to LV range. In the utilized HV SoI process there are numerous HV transistors able to work with gate-drain voltages up to 40, 60 or 80 V, but their maximum gate-source voltage remains limited to about 5.5 V.

Typical LV switch is either a single MOS transistor or a complementary CMOS transmission gate. LV CMOS switches can accept same range of control and input voltages. LV switches are quite universal and simple structures, having a number of derivatives and even patented improvements [1]. Unfortunately, such structures usually cannot be directly adopted as HV switches, and thus HV switches usually have quite different topologies [2]. There are attempts to design HV switches with use of LV devices, but applicability of such circuits seems rather limited [3]. Studies on HV switch topologies have shown that there is number of existing topologies, but they are usually rather specified for specific tasks and various switch applications might require utilization of several different switch topologies.

In general, HV switches are expected to pass high-amplitude signal. Voltage control in presence of limited gate-source voltages of typical HV MOS transistors seem not to be the best possible approach. The idea behind all switch topologies presented in this paper is current-based operation control. The approach is to design a switch as a signal-passing MOS-based switching device equipped with a possibly simple current-voltage converter, connected between gate and source terminals of MOS devices, from which the switching device is composed [4].

2 SWITCH STRUCTURES AND OPERATION

2.1 Switch Test Environment

In order to test presented switch topologies, a set of test-benches has been prepared. Voltage-mode time domain and AC simulations, as well as current-mode time domain simulations have been conducted. Generally, all the test-benches contain a switch as a DUT device, an input signal source (sine or edge-rounded trapezoidal waveform) provided to the switch directly or through a HV unity-gain buffer. Most important part of the test-benches is a current-mode switch-control module (Fig. 1). All simulations have been conducted for the 0.8 um HV BiCMOS SoI process.

2.2 One-transistor-based Switches

The simplest realization of the switch idea is shown in Fig. 2.a. It consists of an MOS transistor as a switching device and a resistive device as a current-voltage converter. A Zener diode is used as a safety device. Unfortunately, this structure, though properly passes its input signal to the output, behaves in undesired manner while in off-state. Fig. 3 shows that there is profound feedthrough from input to output of the Fig. 1.a switch. Fast input transients are able to polarize the switch so that it gets into on-state.

An action that does not require any changes of overall structure of the switch it to reverse its input and output nodes. Fig. 3 seems to show that operation of the reversed switch is proper, now. Though, it is valid only when high-impedance loads are connected to the switch output. If the stage that follows the switch has low input impedance, the flow of the switch control-current may become split between input and output nodes of the switch. Thus, the switch falsifies its output voltage level.

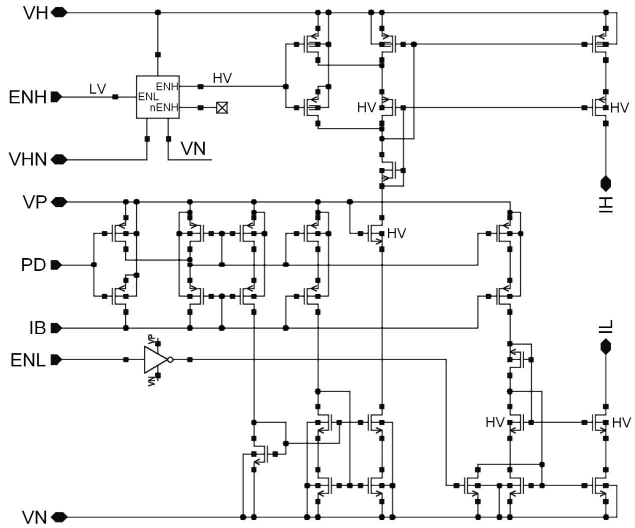

Figure 1: Current-control circuitry used during switch tests.

Also, the presented switch cannot be used for bidirectional input-output isolation. If some voltage change happens at the switch output during the off-state, then this voltage can be passed backwards to the switch input, as was explained in case of the non-reversed version of the switch. Furthermore, this switch cannot be used for current-passing, as it adds its control current to the input node. Though, as long as there is a voltage-mode input connected to the switch and the switch current is limited, it is not a problem.

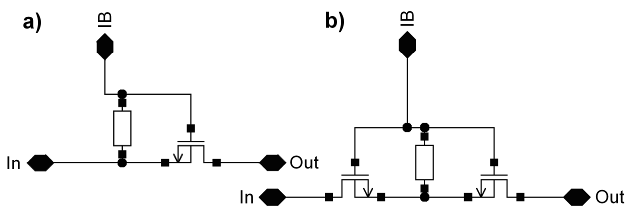

Figure 2: One-transistor (a) and two-transistor based HV switches with one control current.

2.3 Two-transistor-based Switches

As it can be seen, the switch of Fig. 2.a provides only a partial one-way isolation in off-state. Quite straightforward move towards a full two-way isolation switch is just concatenation of two one-transistor switches into one structure. Fig. 2.b presents such a structure. The I/V converting resistor is placed between the switch transistors. Thus, it is isolated from both input and output node during off-state. Moreover, the external switch nodes are drain nodes of the HV MOS transistors, so during off-state both input and output switch nodes can float and follow voltage levels imposed by input and output side circuitry. Quality of voltage-mode operation of the new switch is very similar as in case of reversed version of the Fig. 2.a switch and is satisfactory. Still, the switch presented in Fig. 2.b is unable to properly pass currents, as all its control-current is sunk into the input side circuitry. This is the operation rule that must be changed, if precise passing of current-mode signals by the current-controlled HV switches is required.

As a matter of fact, structures of signal-passing part of switch similar to these presented in Fig. 2 are reported and patented [5]. There are even very similar two-transistor current-passing switch-cores published [6], but with substantially different control-mode applied. These reported switches mainly relay on voltage-mode operation control.

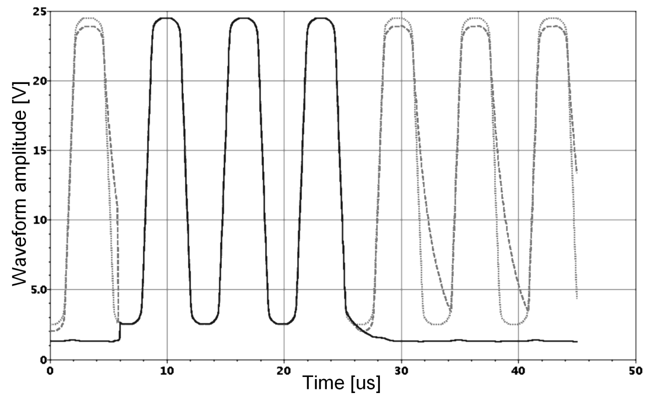

Figure 3: On-state and off-state switch simulations: input signal – dotted line, Fig. 2.a one-transistor switch – dotted line, Fig. 2.b two-transistor switch – solid line.

Fig. 4 presents substantial improvement to the current-mode switch structure. Now, the control current is sourced by one control source and sunk by another one. The price to pay is presence of two control current sources, but the gain is significantly limited current exchange between signal-path (switch input-output path) and the current-control circuitry of the switch.

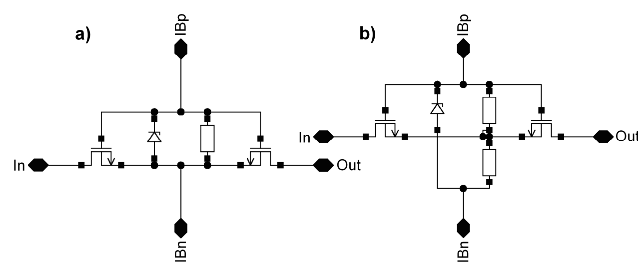

Figure 4: HV switches with two control-currents: simple structure (a), improved structure (b).

Also, while the Fig. 4 switches are in off-state, the control-current path is completely isolated from input and output switch nodes. Switch in Fig. 4.a is a simple version and a Zener diode is a safety device for the switch-core MOS devices and the V/I conversion resistor. Switch presented in Fig. 4.b is very similar, but has one significant asset. It can properly and safely operate while controlled with poorly defined control-current flow. It is possible if resistors in this switch are large enough to get the Zener diode open and conduct. Voltage drop over Zener diodes is quite weakly dependent on their current flow, so if the Zener diode conducts, the voltage drop across the resistors

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is fairly stable. Voltage drop on the single Zener diode is too much for save gate-source driving of MOS transistors. The resistive voltage divider solves this issue. Resistance ratio can be well controlled in semiconductor technologies. Thus, the gate-source voltage of the switch pass-transistors is well defined and these MOS devices can safely operate. Moveover, the Fig. 4.b switch is able to placed more symmetrically in available supply-ground voltage span. Though limited, the current exchange is present in these switches and they should not be used for current switching purposes.

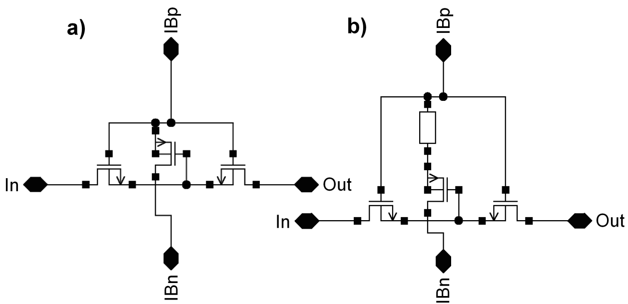

Figure 5: One current-controll switches with stransistor instead of resistors: simple structure (a), control-voltage optimized structure (b).

Still, more switch structure modifications are possible. Fig. 5 presents switches which are attempts of obtaining both complete current-paths isolation and control-current number reduction. In the switch in Fig. 5.a the resistor present in switches in Fig. 2.b, is replaced with an MOS transistor. The I/V converting transistor is gate-source connected with the switch pass-transistors. The HV drain node remains floating and can be used as a control-current removal path, just by being connected to e.g. ground node. The complete – or maybe the best possible - current-flow isolation is obtained, now.

Though, there are some new problems with these switch designs. First, large control-current flow is required to produce large gate-source voltage drop on the I/V converting MOS transistor. This is amended by a switch in Fig. 5.b. An additional resistor is added in series with the I/V MOS transistor, to produce more voltage drop with limited control-current flow. Another problem is fact, that gate-source voltage in MOS transistor with no forced current-flow does not drop to zero but falls to about threshold voltage level.

The off-state is not as firmly defined as in case of switches with I/V resistors, in which no control-current flow means precise 0 V gate-source voltage in switch pass-transistors. For example, switch presented in Fig. 4.a passing 20 uA current cuts it down to 2 nA in 600 ns after cut-off signal, while switch in Fig. 5.a needs 180 us to extinguish same passing current to 2 nA.

Switches shown in Fig. 6 are result of a compromise. A large resistor is added in parallel the the I/V transistor. It passes possibly small amount of current during on-state of switch, but forces 0 V gate-source voltage of switch pass-transistors during off-state. Unfortunately, big resistor may casue larger parasitic capacitances. Also, current flow isolation is lost, again. Still, different approach is needed to obtain properly operating current-mode current-controlled HV switches.

Fig. 7 presents a modified switch structure. Now there are two control currents, but signal and switch curren-flows are izolated and there is proper off-state control of the switch. There are two possible modes of circuit operation. In one mode a current flows through the I/V converting transistor only during state, and a current through the right resistor in Fig. 7 flows only during the off-state, pushing gate-source voltage of switch pass-transistor down to 0 V.

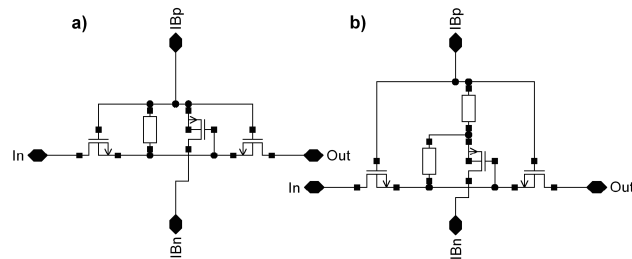

Figure 6: Switches with additional shunt resistors: simple structure (a), control-voltage optimized structure (b).

In the other mode, the current that flows through the I/V transistor is a constant bias current, so that this transistor gate-source voltage is firmly defined, while the current that flows through the rignt resistor, is present only during the off-state, as in the previou mode. The switch structure is more complicated, but finally the set of properties required for current-mode switch operation is obtained. Its worth mentioning, this switch can also be controlled with application of control-circuit presented in Fig. 1.

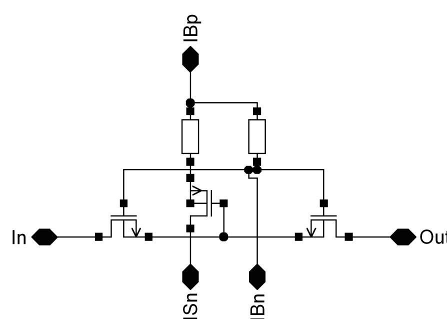

Figure 7: Switch for current-switching applications.

The presented switches are designed in the HV SoI process, in which precise current-mirrors powered from HV supply node are feasible. In case of other HV processes without such possibilities, PMOS versions of switches with one control-current may be used, so that only low-side current-control is required. Unfortunately, application of PMOS transistors makes the switches larger and slower. This was tested and bandwith of the switches is indeed over three times lower in case of PMOS-based switches.

3 APPLICATIONS

HV switches can be used both as power switches in power-management related application and as signal-path control devices. Authors found these switches especially handy in internal test-circuitry, when several HV voltage and current waveforms, DC levels and control signal had to be probed and provided to a kind of interface circuitry, which directs mentioned signals one by one to a selected ASIC node, for further external assessment.

Sometimes additional output-stages can be added to current-mirrors and some current signal can be probed constantly. In other cases, copy preparation would require implementation of whole HV current mirrors, which might deteriorate quality of final output current signals. It was found to be more effective to temporality redirect some on-chip generated current for test-intended probing. Some control current-mirrors must be added for switches, but they are separate from current signal-paths. Also, all the switches are connected to the signal-paths, both voltage- and current-mode, only with one terminal – drains of HV MOS transistors, which are floating during switch off-state.

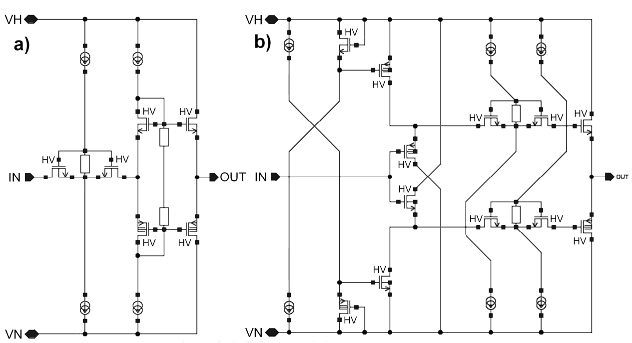

Figure 8: Examples of switch integration into HV blocks: a typical switch and a vertical switch application (a), complete switches installed inside the buffer (b).

4 INTEGRATION

Application of the presented switches inside signal-path of HV ASIC functional blocks is connected with specific ways of integrating these switches with or into function blocks. Typical way of switch implementation is placing it between other signal processing blocks in signal-paths. But this is not always a way to follow. For example, there is a high input-impedance voltage buffer in the signal-path and it needs to be disconnected from its input signal to keep constant voltage at its output. Application of a simple switch, like one used in Fig. 8.a would disable the high input impedance property of the buffer, as this switch itself sinks or sources some amounts of current to and from the input node of a complete switch-buffer block. To solve this issue either a more complex switch can be used or simple switches might be used, but inside the buffer, so that the high input impedance of the switch-buffer block is retained.

Such a structure is presented in Fig. 8.b. There are two simple switches used, so as to pass the input stage signals that drive the output stage of the buffer. In Fig. 8.a there is another structure that may be considered as a kind of a vertical current-controlled switch. There is a resistive connection between two input-output stage signal-passing paths in the buffer. If a high resistance is implemented this way, operation of the whole buffer remains almost unchanged. But, when the buffer goes into power down state and all its bias currents are stopped, this resistive connection forces gate-source voltages of the input- and output-stage buffer transistors to fall to 0 V, instead of falling to about the threshold voltage level. This way high input- and output-impedance is achieved in the down-powered buffer. Now, possible voltage changes at the input- and output-nodes of the buffer in power-down state do not cause current flows inside the buffer structure.

5 CONCLUSIONS

The current-mode control of HV switches in SoI technologies offers possibility to design a set of rather non-complicated and handy switches. These switches can be used in both voltage- and current-mode signal-paths.

It is remarkable that all different switch topologies, can be driven with same control circuitry. This asset makes the presented switches easily applicable and interchangeable.

An idea of vertical current controlled switch is introduced by means of using topology resemblance between input- and output-stages of unity-gain HV buffer and HV switches. This way, a very limited modification is able to endow the buffer with new functionality.

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