Bootstrapped Low-Voltage Analog Switches

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ABSTRACT

Novel low-voltage constant-impedance analog switch circuits are proposed. The switch element is a single MOSFET, and constant-impedance operation is obtained using simple circuits to adjust the gate and bulk voltages relative to the switched signal. Low-voltage (1-volt) operation is made feasible by employing a feedback loop. The gate oxide will not be subject to voltages exceeding the supply voltage difference.

Realistic switches have been simulated with HSPICE. The simulations show that the switch circuits operate very well, even when the supply voltage approaches the technology's threshold voltage.

1. INTRODUCTION

Technology constraints and battery-powered operation require that low-voltage analog circuits be designed. Whereas low-voltage operation is associated with many advantages for digital circuits, it generally complicates the design of analog circuits. When the supply voltage is lowered, not only does it become increasingly difficult to maintain the same (high) level of SNDR performance, but even the functionality of the circuit may be hard to preserve.

High-performance analog circuits are usually implemented as discrete-time circuits, often as switched-capacitor (SC) circuits. The design of analog switches which conduct reliably in the rail-to-rail range is the main difficulty in the design of low-voltage SC circuits. Switched-opamp and other dedicated low-voltage SC circuit techniques that avoid the need for rail-to-rail switching have been proposed \[1, 2\]. Although such techniques are useful and commercially utilized, it should be understood that they represent a tradeoff with respect to speed, power consumption, and design flexibility. This paper describes simple circuits that implement the rail-to-rail switching function, thereby facilitating the implementation of general low-voltage SC circuits.

2. MOSFET-BASED ANALOG SWITCHES

A MOSFET in itself can be used as an analog switch. The drain and source terminals are the two switch terminals, and the gate and bulk terminals are used to control the conductivity of the channel between the two switch terminals. Unfortunately, the MOSFET switch's conductivity depends not on the absolute potential of the control terminals, but on their potentials relative to the conductive channel's potential. Despite of this property, MOSFET switches are, for simplicity, often controlled by CMOS-logic clock signals having fixed potentials in the on and off states. The conductance of such a MOSFET switch is strongly signal-dependent (Fig. 1).

An NMOS and a PMOS switch can be used in parallel to form a transmission-gate switch having a region where the conductance is approximately signal-independent. However, when the supply voltage is lower than the sum of the two transistors' threshold voltages (absolute values), this region not only vanishes, but is replaced by a region (in the middle of the supply-voltage range) where the switch does not conduct reliably (Fig. 2).

2.1. Low-Voltage Operation

If the supply voltage is low (say, 1.2 volts) and low-threshold-voltage MOSFETs (which are subject to leakage problems) are not available, rail-to-rail switching operation requires that control signals exceeding the supply-voltage range be generated. Clock-signal doublers have been proposed \[3\], but in a single-well technology they can be used only for MOSFETs of one type\(^2\); hence

\(^1\) Occasionally, the bulk terminal is called the back-gate terminal. For single-well technologies, the bulk may be the substrate, in which case it cannot be controlled separately for each MOSFET.

\(^2\) In a P-well technology, doubled clock signals can be generated only for NMOS switches. The problem is related to the forward-biasing of PN
the switch conductance will be strongly signal-dependent. Another disadvantage is that the gate oxide will be subject to voltages of up to twice the supply-voltage difference, which may cause hot-electron effects and possibly permanent breakdown of the gate oxide.

3. BOOTSTRAPPED SWITCH

To obtain constant-conductance operation the gate-to-channel voltage should preferably be held constant during the on state. This can be obtained using a bootstrap technique (Fig. 3). The technique is discussed in Section 11.3 in [4], but a circuit realization is unfortunately not provided.

In the off state the bootstrap capacitor \( C_b \) is charged to the supply-voltage difference, and ideally it will act as a floating battery in the on state \( V_T \). The NMOS switch \( N_0 \) will be non-conducting in the off state because \( sw_3 \) connects the gate terminal to the low supply potential \( V_{ss} \). In the on state, the switches \( sw_1 \) and \( sw_2 \) connect the fully-charged bootstrap capacitor \( C_b \) between \( N_0 \)'s gate and source terminals. Assuming that the stray capacitance loading of \( C_b \) is small, \( N_0 \)'s overdrive will be nearly constant and the switch's on-state conductance will be approximately (neglecting the body effect and the stray load of \( C_b \))

\[
g_{\text{switch}} = \mu C_{ox} \frac{W}{L} (V_{dd} - V_{ss} - V_{TN})
\]

(1)

Hence, if \( V_{dd} - V_{ss} > V_{TN} \), the bootstrapped switch will conduct in the entire supply-voltage range, and its conductance will be nearly signal-independent. Clearly, the difficulty lies in the implementation of the internal switches, particularly (but not exclusively) \( sw_1 \) which must also be able to conduct in the rail-to-rail range.

3.1. Simple Implementation

Fig. 4 shows a simple implementation of the bootstrapped switch, where \( sw_1 \) is implemented as a bootstrapped NMOS switch \( N_1 \). The main difference between \( N_1 \) and \( N_0 \) is that \( N_1 \)'s source terminal is connected to \( V_{ss} \) in the off state, whereas the switch terminals, \( V_{in.a} \) and \( V_{in.b} \), are floating.

Switches \( sw_3 \) and \( sw_5 \) implement trivial switching functions, hence they are implemented as simple NMOS switches \( N_3 \) and \( N_5 \). At first sight, the design of \( sw_4 \) may also appear to be trivial, but this is not the case. Unfortunately, \( sw_4 \) cannot be implemented as a simple PMOS switch controlled by CMOS logic because it would leak during \( V_T \) when the bootstrap capacitor provides a potential that exceeds \( V_{dd} \). Instead, \( sw_4 \) may be implemented as an NMOS switch \( N_4 \), which is controlled by a level-shifted clock signal having levels \( V_{dd} \) and \( 2V_{dd} \) (assuming \( V_{ss} = 0 \)). The level shifter is based on the widely-used Nakagome charge pump [5].

As illustrated, \( sw_2 \) can be implemented as a simple PMOS switch \( P_2 \). Because \( P_2 \)'s channel potential will exceed \( V_{dd} \) in the on state \( V_T \), it is necessary to bias its bulk terminal to a voltage which is at least as high as that provided by the bootstrap capacitor. A simple option is to connect the bulk terminal to the source terminal (as shown), but it may be better to connect it to \( 2V_{dd} \) which can be generated using the level shifter and a few extra transistors (traditional voltage doubler, not shown). The biased-well PMOS implementation of \( sw_2 \) is a considerable drawback for the circuit because it implies that \( N_0 \) cannot be implemented in a separate well (using a single-well technology); consequently, \( N_0 \) cannot be compensated for the body effect. Unfortunately, \( sw_2 \) cannot be designed as an NMOS switch because that would require that large clock signals be generated.

3.2. Improved Implementation

Fig. 5 shows an improved implementation of the switch. \( N_{lb} \) is a simple NMOS switch which should be included if the supply voltage is only slightly higher than the PMOS threshold voltage. \( N_{lb} \) prevents switch malfunction which may occur if clock feedthrough is allowed to reduce the channel potential of \( P_2 \) to a level where it does not turn on, in which case \( N_1 \) (and hence \( N_0 \)) will not turn on either.

A more serious problem of the simple implementation (Fig. 4) is that the gate oxide of \( N_3 \) and \( P_2 \) is subject to voltages that exceed the supply voltage difference. This may become inadvisable in the foreseeable future. \( N_3 \) is easily protected by including the cascade device NMOS \( N_{sb} \). The gate oxide of \( P_2 \) is more difficult to protect because the high stress occurs when it conducts. The problem is solved by operating \( P_2 \) with a constant overdrive. \( N_2 \) is a bootstrapped switch that connects \( C_b \) between the gate and source terminals of \( P_2 \), whereby \( P_2 \) also becomes bootstrapped. The two interconnected bootstrap loops do not lock automatically, which is why the small capacitor \( C_b \) is needed to initiate the switch's on

\[ V_{in.a} \]
\[ \phi \]
\[ V_{dd} \]
\[ \phi \]
\[ sw_1 \}
\[ sw_2 \}
\[ sw_3 \}
\[ sw_4 \}
\[ sw_5 \}
\[ C_b \]
\[ V_{ss} \]
\[ V_{ss} \]

Figure 4: Bootstrapped switch: simple implementation.

\[ V_{in.b} \]
\[ \phi \]
\[ V_{dd} \]
\[ \phi \]
\[ sw_1 \}
\[ sw_2 \}
\[ sw_3 \}
\[ sw_4 \}
\[ sw_5 \}
\[ C_b \]
\[ V_{ss} \]
\[ V_{ss} \]

Figure 3: Bootstrapped switch: fundamental principle.

\[ V_{in.a} \]
\[ \phi \]
\[ V_{dd} \]
\[ \phi \]
\[ sw_1 \}
\[ sw_2 \}
\[ sw_3 \}
\[ sw_4 \}
\[ sw_5 \}
\[ C_b \]
\[ V_{ss} \]
\[ V_{ss} \]

Figure 4: Bootstrapped switch: simple implementation.
state \( \phi \). P2 is turned off (and \( C_2 \) is precharged) by the simple PMOS switch P2b.

A similar switch has been developed and published in parallel to this work [6]. The only differences are that it lacks N1b (which was unnecessary because the supply voltage was fairly high, 1.5 V) and that it fails to effectively protect the gate oxide of P2.

4. BODY EFFECT COMPENSATION
At very low supply voltages, and in other critical situations, the MOSFET switch's body effect may represent an intolerable non-linearity. As discussed above, it is the PMOS implementation of sw2 which prevents the bootstrapped switch (Fig. 3) from being compensated for the body effect when implemented in a single-well technology. An alternative bootstrap topology, which is not subject to this problem, is shown in Fig. 6.

![Figure 6: Body-effect-compensated bootstrapped switch.](image)

The fundamental difference is that the bootstrap capacitor is connected directly to the gate terminal of P0. sw5 turns off P0 in the off state, and that requires \( C_b \) to be charged between \( V_{dd} \) and \( 2V_{dd} \). The high potential \( 2V_{dd} \) is generated by the charge pump. In the on state, sw1 and sw2 close the bootstrap loop. Notice that P0 is compensated for the body effect by connecting the bulk terminal to \( V_{in,off} \) in the on state. sw2 and sw3 can, in principle, be a short and an open circuit respectively, but they should be real switches to avoid loading the charge pump by the well in which P0 is implemented.

4.1. Implementation
Fig. 7 shows an implementation of the switch. Here, sw4 is implemented as a PMOS P4, which operates as a rectifier for the alternating voltage provided by the charge pump. sw3 and sw5 are implemented as the simple PMOS switches P3 and P5a. The gate oxide of P5a is protected by the cascode device PMOS P5b. sw1 can, for example, be implemented as a PMOS device controlled by the same gate signal as P0 (not shown). sw2 is the only switch that may be difficult to design because it is exposed to the high potential from the charge pump. If the gate oxide is robust, sw2 can be implemented as an NMOS N2 with its gate terminal connected to "Node A" in the charge pump (not used in the shown implementation). Alternatively, if the gate oxide is sensitive and the supply voltage is fairly high, sw2 may be designed as a transmission-gate-type switch. The shown implementation of sw1 and sw2 illustrates an option for use in the most complicated situation where the gate oxide is fragile and the supply voltage is only slightly higher than the threshold voltage.

In this case, sw2 can be an NMOS N2 controlled by a gate signal which is \( V_{in,off} \) in the off state and \( V_{in,off}+V_{dd} \) in the on state. This signal is generated by the bootstrapped switch shown in Fig. 5, where it is available at the source terminal of P2. If this switch (Fig. 5) is implemented anyway, sw1 can be implemented simply as a bootstrapped switch N1' controlled by the signal provided at the drain terminal of P2.

![Figure 7: Low-voltage low-stress (gate oxide) implementation.](image)

5. SIMULATION RESULTS
The switches shown in Figs. 5 and 7 have been simulated with HSPICE using BSIM3v3 transistor models for a 0.6\textmu m technology, in which the threshold voltages were approximately 0.8 V and \(-0.85\) V for NMOS and PMOS transistors, respectively. All transistors were minimum-length, and N0 and P0 were respectively 10 \textmu m and 30 \textmu m wide. Except for N1, N1', and N2' which were 3 \textmu m wide, all internal NMOS transistors were 1 \textmu m wide, and all internal PMOS transistors were 3 \textmu m wide. All capacitors were 1 \textmu F, except \( C_2 \) which was only 0.1 \textmu F. The switches were generally simple to design, and very little optimization was performed for these simulations.

The generation of the non-overlapping clock signals is, however, a design aspect which can make a great difference in the performance. The inverter shown in Figs. 5 and 7 was used to drive the output of the non-overlapping clock phases is necessary to prevent the 1 \textmu F capacitors from being partially discharged in the transition between the two states \( \phi \) and \( \overline{\phi} \). This is advisable even for the charge pump.
an SR latch with delayed outputs\textsuperscript{9}, and all internal switches were
driven by the thereby generated non-overlapping clock phases \( \Phi \) and \( \Phi \) (each clock phase was generated both as an inverted and as an
noninverted voltage signal).

The offset (50 mV) represents a charge portion equivalent to the
inversion charge accumulated in the conductive channel during the on state.
This charge flows to the gate of \( N_0 \) to charge the gate-to-channel "capaci-
tor."

The switch's impedance is very well-behaved; the slight droop in
impedance is caused by the corresponding droop in the gate-to-source voltage. The switch's operation is reliable for supply volt-
ages as low as 0.9-1.0 V, for which the switch impedance is in the
order of 10 k\( \Omega \).

If large (low-impedance) switches are designed without in-
creasing \( C_b \) proportionally, the gate-to-source voltage may have
a considerable droop. The switch, however, can still be designed
such that the impedance will be nearly signal-independent. By
connecting a small NMOS device, say \( N_6 \), in parallel with \( P_0 \),
and by connecting \( N_6 \)'s gate terminal to the gate terminal of \( N_1^* \) in
Fig. 7, a bootstrapped "transmission-gate" switch with an ap-
propriate "mix" of the impedance curves in Figs. 8 and 9 can be
designed.

6. CONCLUSION

Boostrapping techniques are suitable for the linearization of MOS-
FET switches. It was demonstrated that bootstrapped switches
with a reliable linear switching operation can be implemented in
a standard CMOS technology, even when the supply voltage is as
low as 1 volt. Using these switches, low-voltage SC circuits can
be implemented in any usual topology.

The best performance is obtained if the switching MOSFET is
compensated for the body effect. This is feasible also in single-
well technologies, using a new bootstrap topology (Fig. 6) where
the bootstrap capacitor is connected directly to the gate of the
switching MOSFET. The switch circuits can be designed such
that the gate oxide is not subject to voltages exceeding the supply volt-
age difference. This requires the use of several transistors, but the
total chip area required is modest.

The switch’s remarkable linearity makes it a prime candidate
for use in circuits that sample continuous-time signals (low voltage or not). A patent is pending on the described circuits.

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