

Texas Instruments Solution for Undershoot Protection for Bus Switches

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ABSTRACT

Three solutions for undershoot protection (Schottky diode, charge pump, and active clamp) are discussed. Their advantages and disadvantages are presented, as well as a comparison of significant characteristics of each solution. Laboratory test data confirm the superior performance of the TI device with the active-clamp undershoot-protection feature.

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Introduction

The TI™ CBT/CBTLV bus-switch family has become an indispensable solution in high-performance personal-computer (PC), data-communications, and consumer applications. In some applications, due to various system design techniques, undershoot events occur. This undershoot forces the switch on, intermittently, over a short time interval. When a bus switch is disabled, an input undershoot that exceeds its threshold voltage V_T can turn on the pass transistor. This unwanted condition causes severe data errors on the outputs.

TI has a new, active-clamp undershoot-protection feature in the bus-switch family, designated K, i.e., CBTK. This application report discusses various options for undershoot protection, including their advantages and disadvantages. Laboratory test results demonstrate the superior performance of the new CBTK devices with the undershoot-protection feature.

Background

What Happens to the Bus Switches When Undershoot Occurs

The bus switch consists of a large, but simple, NMOS transistor that passes data. Figure 1 illustrates a simple bus switch. The gate of the NMOS transistor is controlled by an enable signal. When the gate voltage is low, the switch is off.

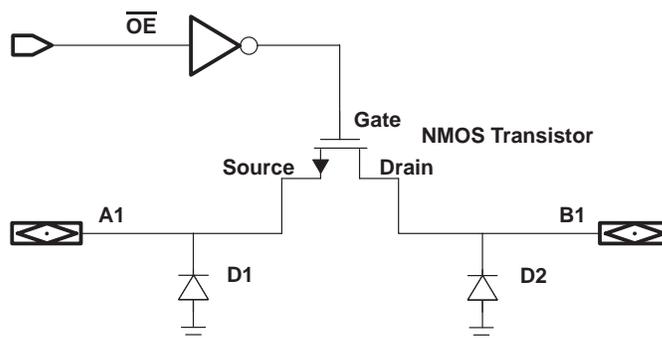


Figure 1. Basic NMOS-Transistor Bus Switch

When the gate voltage is high, the switch is on. The threshold voltage V_T of an NMOS transistor is approximately +650 mV. When V_{GS} (gate-source voltage, $V_G - V_S$) is greater than V_T , the switch is turned on. In the enabled state, undershoot is not a problem. But, when the switch is disabled, a negative voltage on the bus could turn on the switch, causing a data error.

Two different situations can exist when undershoot occurs. The first situation occurs when the source node voltage (V_S) becomes lower than the gate voltage (V_G). Any undershoot on the source node (V_S) greater than or equal to +650 mV creates a positive V_{GS} , which is greater than V_T . This turns on the switch, and the two buses are no longer isolated. Corruption of data is inevitable.

In the second situation, a parasitic npn transistor is formed in the NMOS transistor during manufacturing. Figure 2 shows the cross-sectional view of an NMOS transistor. The emitter is the n⁺ source/drain implant, the base is the p-type substrate, and the collector is the n⁺ source/drain implant. When undershoot below ground occurs on the source node, because the substrate is at 0 V, a positive V_{be} is created on the parasitic npn transistor and causes the transistor to conduct. With β of approximately 10, a small amount of base current generates enough collector current to establish a continuous flow from collector to emitter, i.e., from drain to source. So the switch is on again, instead of being off, creating a major data error.

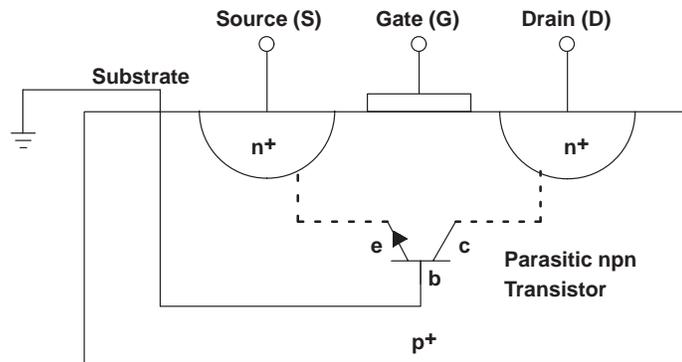


Figure 2. Cross-Sectional View of an NMOS Transistor

Undershoot Event Cases

Termination is an important consideration in signal integrity. Usually, undershoot occurs when a bus is not terminated or is poorly terminated. Signals with very fast edge rates also can degrade signal quality by generating undershoots. Good transmission-line designs can resolve these issues, but some systems, such as a PCI bus, are designed to have a reflected wave. To achieve very high speed using low power, the PCI bus is not terminated. Reflections are not eliminated, by design, but reflections are expected. These reflections can cause severe undershoot conditions that force the bus switch to function improperly.

Techniques for Undershoot Protection

Three main techniques provide undershoot protection: Schottky-diode solution (CBTS), charge-pump solution (none), and active-clamp solution (CBTK). TI, as a world leader in bus-switch technology, designed the CBTK devices to solve undershoot problems. This active clamp feature offers excellent protection against high-current undershoot events. The comparisons in the following paragraphs prove CBTK to be the best solution for undershoot protection.

Schottky-Diode Solution

Figure 3 shows the basic NMOS crossbar switch with Schottky diodes. The n-channel pass-transistor source and drain are connected to two different buses. The gate of the pass transistor is controlled by the \overline{OE} signal that is generated from the output-enable circuit. When the gate voltage is high, the switch is closed. When the gate voltage is low, the switch is open. The undershoot event does not affect performance of the switch when the switch is on. But, if undershoots occur when the bus switch is off, passing unwanted data can cause a data error. To prevent this, two Schottky diodes are connected from the source and drain to ground. When one of the buses has negative voltage that exceeds the forward turnon voltage of the Schottky diode, the diode turns on and clamps the source or drain voltage of the NMOS switch, keeping the buses isolated.

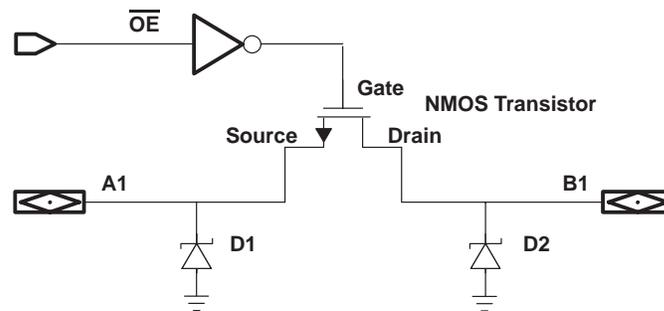


Figure 3. Basic NMOS Switch With Schottky-Diode Clamps

A Schottky diode clamp has the following advantages and disadvantages:

- Advantages
 - Low power requirement
 - Some undershoot protection
 - Bidirectional, both ports protected
- Disadvantages
 - Slow to react to undershoot voltages with fast edge rates. This could cause the n-channel pass transistor to turn on and affect the buses.
 - No effect on the parasitic npn transistor. Because the parasitic transistor's base is the substrate that is at ground, the undershoot turns on the transistor and a large current corrupts the data.
 - Significant addition of input/output capacitance

Charge-Pump Solution

In this implementation, a charge pump with a negative voltage controls the substrate voltage and the gate voltage of the transistor. During an undershoot event, the charge pump keeps the gate voltage and the substrate voltage negative, so both of them are off.

The advantages and disadvantages of the charge pump are:

- Advantages
 - Excellent undershoot protection
 - Lower input/output capacitance
 - Low I_{off}
 - Bidirectional, both ports protected
- Disadvantages
 - Significantly high I_{CC}
 - Higher cost due to chip size increase for the charge-pump circuit

Active-Clamp Solution

This technology integrates an active-clamp undershoot-protection circuit on both ports. In the active-clamp circuit, a bias generator sets a voltage slightly above ground, which allows the active-clamp pullup voltage to turn on during an undershoot event. This clamp counteracts the undershoot voltage and limits V_{GS} , V_{GD} of the n-channel, and V_{be} of the parasitic npn transistor. Figure 4 shows the basic NMOS switch with active-clamp pullup circuits.

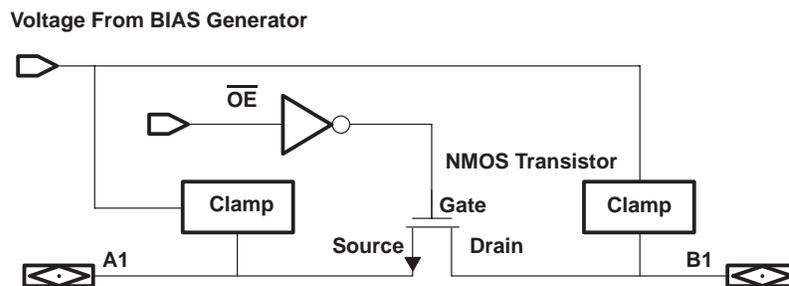


Figure 4. Basic NMOS Switch With Active-Clamp Pullup Circuits

Advantages and one disadvantage of the active-clamp solution are:

- Advantages
 - Excellent undershoot protection
 - Capacitance is low. Minimal capacitance is added.
 - Overvoltage-tolerant I/Os
 - Faster enable/disable switching speed than the Schottky solution
 - Less power required
 - Low I_{off}
 - Both ports protected
- Disadvantage
 - Chip-size increased

Table 1 provides a comparison of significant characteristics of these three undershoot-protection technologies. Different techniques of undershoot protection provide varying degrees of protection with different tradeoffs.

The comparison in Table 1 indicates that the Schottky-diode solution handles only minimal-undershoot events.

The charge-pump solution provides excellent undershoot protection, but has high I_{CC} and high power consumption. Therefore, it is not ideal for mobile and power-consumption-sensitive applications.

The active-clamp solution provides excellent undershoot protection and consumes less power. Moreover, it is overvoltage tolerant, which allows compatible operation in mixed-voltage systems.

Table 1. Comparisons of Undershoot-Protection Technologies

CHARACTERISTICS	SCHOTTKY DIODE (CBTS)	CHARGE PUMP	ACTIVE CLAMP (CBTK)
Undershoot protection	Good. Protection on both ports slows to react with fast edge rates. No effect on parasitic transistor.	Excellent protection on both ports	Excellent protection on both ports
I_{CC}	Low ($\leq 10 \mu\text{A}$)	Very high ($> 100 \mu\text{A}$)	Low ($\leq 20 \mu\text{A}$)
Capacitance	High (9 pF)	Low (5 pF)	Low (5 pF)
I_{off}	No I_{off} specification	Low (10 μA)	Low (10 μA)
Overvoltage tolerance	No	No	Yes

Laboratory Comparison of Various Device Options

Laboratory testing demonstrated the excellent undershoot-handling capability of the active-clamp circuit (CBTK). Figure 5 shows the test setup. Three devices (CBT6800, CBTS6800, and CBTK6800) were tested with one output switching. A valid high logic level is established on port B by charging a load capacitor on port B to 5.5 V. The bus switch was disabled and an input with an undershoot of -2 V and 20-ns pulse duration was applied. The output of each device was recorded. The standard CBT6800 device turned on as soon as the undershoot event occurred and the capacitor discharged. The Schottky-diode version (CBTS6800) turned on slowly and discharged the capacitor. In contrast, the CBTK effectively clamped the undershoot and maintained excellent signal integrity on port B.

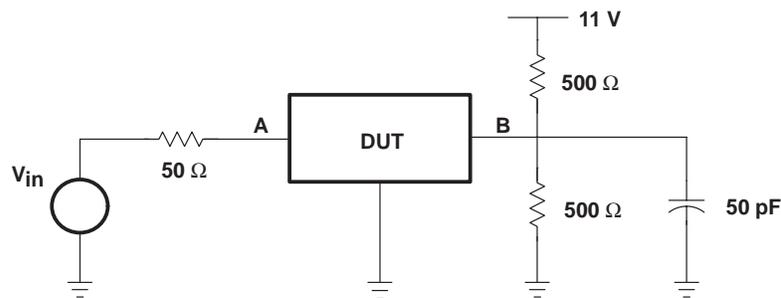


Figure 5. Test Setup for the Undershoot Test

Figure 6 shows the output waveforms from the test. The active-clamp solution performance is much superior compared to the standard product without the clamping feature. The CBTS offers minimal protection. TI provides bus switches with Schottky diodes (CBTS) and active-clamp undershoot-protection (CBTK) features.

Due to an undesirably high I_{CC} , the charge-pump solution is not offered by TI.

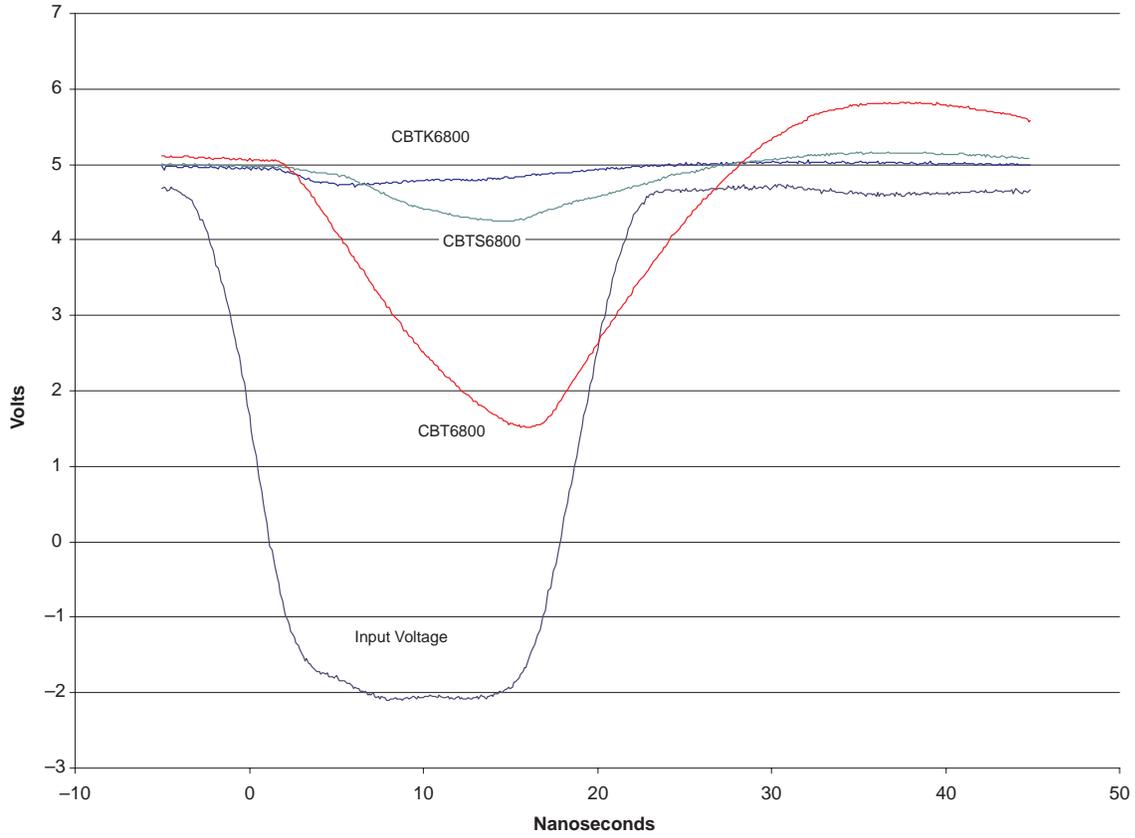


Figure 6. Output Waveforms During Testing of Undershoot Protection of Different Crossbar-Switch Solutions

Conclusion

Systems migrating to lower voltages and improved speeds require bus switches that can prevent unwanted undershoots. Good design techniques can solve problems associated with transmission lines, but systems with an intentionally reflected wave have undershoots.

The TI active-clamp solution provides excellent undershoot protection, while consuming less power, a desirable feature in today's power-hungry applications. Combined with low power consumption and overvoltage tolerance, the CBTK device is the ultimate solution for undershoot events. TI, as a leading supplier of bus switches, offers innovative functions from multiplexers to simple FET switches in a variety of bit widths. The active-clamp feature, implemented across the majority of functions in 5-V and 3.3-V devices, provides greater flexibility in designing systems.

Glossary

β (beta)	(I_C/I_B) Gain factor of a bipolar junction transistor
CBT	Crossbar technology
CBTLV	Low-voltage crossbar technology
CBTK	Crossbar technology with active-clamp undershoot protection
CBTS	Crossbar technology with Schottky-diode undershoot protection
I_{CC}	Supply current
I_{off}	Input/output power-off leakage current
NMOS	N-channel metal-oxide semiconductor
PC	Personal computer
V_{be}	Difference between base voltage and emitter voltage
V_G	Gate voltage
V_S	Source voltage
V_{GS}	Difference between gate voltage and source voltage
V_{GD}	Difference between gate voltage and drain voltage
V_T	Threshold voltage

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