New-generation ESD-protection devices need no $V_{CC}$ connection

By Roger Liang
*High Volume Linear*

Introduction

As digital and analog ICs grow increasingly sensitive to electrostatic-discharge (ESD) damage due to their shrinking process nodes, discrete ESD-protection diodes have become necessary to guarantee sufficient system-level ESD protection. In the past, the $V_{CC}$ connection was added to diodes to reduce their junction capacitance. With the advent of new diode technology, this is no longer required. This article explains the $V_{CC}$ connection’s necessity in the past and the advantages of not having to use it in the present.

ESD is the release of built-up static electricity when two objects of different electric potential come into contact. For example, on a dry winter day, up to 20 kV of ESD can build up simply from packing a printed circuit board (PCB) into a foam-lined box. To ensure that electronic end equipment is immune to everyday ESD events, discrete diodes with more robust ESD ratings than the standard 2-kV human-body model (HBM) are often required. The ESD rating of discrete diodes is directly proportional to the area of the diode’s p-n junction; however, the bigger the junction, the larger is the parasitic capacitance. In order not to compromise a diode’s ESD rating, adding a $V_{CC}$ connection is one IC design technique that effectively decreases the diode’s parasitic capacitance, but at the risk of damaging any other device connected to $V_{CC}$. However, recent improvements in process technologies have allowed diode designers to remove the $V_{CC}$ connection while still guaranteeing a high ESD rating with low capacitance.

Diode characteristics

A diode is the most basic semiconductor device. It is made from a p-type and an n-type junction and has two terminals: an anode at the p-type end and a cathode at the n-type end (Figure 1). When a large enough voltage is applied from the cathode to the anode (reverse biasing), the diode enters its breakdown region and, in theory, can conduct an infinite amount of current at zero resistance. A voltage applied in the other direction (forward biasing) causes the diode to enter its forward-conducting region. Figure 2 shows the IV curve of a basic diode with the anode grounded and voltage swept across the cathode. While there are many types of diodes made for different applications, the topic under discussion is ultrafast-response diodes made for ESD-protection applications. These diodes can respond to a high ESD voltage very quickly and clamp thousands of volts to just tens of volts in a matter of nanoseconds by shunting the ESD current to ground.

There are two contributing factors to a diode’s parasitic capacitance: junction capacitance (due to charge variation in the depletion layer) and diffusion capacitance (due to excess carriers in the quasi-neutral region). Junction capacitance dominates in the reverse-biased region, which is the
usual application region for ESD diodes. The junction capacitance of a diode is characterized by

\[ C_j(V) = A \sqrt{\frac{e_{Si} q}{2} \left( \frac{N_A N_D}{N_A + N_D} \right) \left( \frac{1}{\sqrt{\phi_0 - V_A}} \right)} \]

with the following definitions:

- \( A \) is the area of the junction.
- \( e_{Si} \) is the dielectric constant of silicon.
- \( q \) is one coulomb charge.
- \( N_A \) is the acceptor doping concentration.
- \( N_D \) is the donor doping concentration.
- \( \phi_0 \) is the built-in voltage of the junction.
- \( V_A \) is the bias voltage applied on the junction.

On the application level, the more \( V_A \) is applied, the lower the junction capacitance will be (Figure 3). This is the reason why older diode technology required a \( V_{CC} \) bias in order to adjust \( V_A \) and bring down the parasitic capacitance. Having a \( V_{CC} \) connection also allows a systems engineer to add a large capacitor at the \( V_{CC} \) node (Figure 4), which serves as a charge reservoir to absorb some extra ESD energy, thus increasing ESD protection incrementally.
Using high-speed diodes for ESD protection

To design a low-capacitance diode structure with a high ESD rating, a three-diode approach is often used (see Figures 5 and 6), for three reasons:

1. A diode can withstand much more current in the forward-conducting region than in the reverse-breakdown region.
2. Hiding Diode 1 with the Zener diode protects against positive ESD strikes.
3. Hiding Diode 2 protects against negative ESD strikes.

Two smaller hiding diodes are connected in series with a larger Zener diode because the hiding diodes’ smaller capacitance effectively hides the Zener diode’s large capacitance due to the series structure. During a positive ESD event, Hiding Diode 1 enters its forward-conducting region. The Zener diode enters its reverse-breakdown region, creating a path for ESD current to be shunted to ground without entering the device under protection. The size of the larger Zener diode allows it to withstand the large amount of current flow in its breakdown region. During a negative ESD event, Hiding Diode 2 enters its forward-conducting region and channels ESD energy directly to ground. During either event, the hiding diodes can handle the large amount of ESD current flow because they never break down and enter only the forward-conducting region.

Advantages of not using a \( V_{CC} \) connection

Diode-fabrication technology has made great improvements over the past few years that have enabled a lower junction capacitance without sacrificing a high ESD rating. These improvements are:

- Moving away from a lateral diode structure to a vertical diode structure
- Increased unit area ESD performance
- Less \( N_A \) and \( N_D \) doping to reach the same forward and breakdown voltages

These improvements mean a \( V_{CC} \) connection is no longer required to bring down the junction capacitance to support high-speed interfaces. Having no \( V_{CC} \) connection gives the systems engineer the following three advantages.

1. No current leakage into internal power supply

If a higher-voltage input signal is connected to the ESD diode I/O with a lower \( V_{CC} \) level, signal current could leak through Hiding Diode 1 into the \( V_{CC} \) and other devices connected on that node (Figure 7). This could damage either...
the power supply or any device connected to it. If $V_{CC}$ is not connected to the ESD diode, there is no such worry.

2. No ESD damage to internal power supply
During a positive ESD strike, $V_{CC}$ is along the ESD current's discharge path and experiences a voltage level that is one $V_P$ (~0.5 to 0.7 V) drop below the clamping voltage at the I/O. Although the power supply is very robust against ESD due to the shunt capacitor, this raised voltage level could very likely damage any device powered by the $V_{CC}$ (Figure 8). Again, if $V_{CC}$ is not connected to the ESD diode, there is no such worry.

3. No external capacitor necessary
ESD-diode process development at Texas Instruments (TI) is focusing on strengthening the overall p-n structure so it can withstand more ESD voltage. With TI’s new generation of ESD-protection diodes rated as high as 30 kV, an extra capacitor can improve the overall ESD rating only marginally. Using one will generally reach a point of diminishing returns. Not having a capacitor reduces the bill of materials count, saves on cost, and allows more PCB space for other critical devices.

Examples of TI’s new-generation ESD-protection devices
TI’s TPD2E2U06 ESD-protection device is a noteworthy example of the improvements made in diode technology. Unlike its predecessor, the TPD2E001 does not require a $V_{CC}$ connection but maintains the same capacitance, clamps to a lower voltage, and increases the ESD rating threefold. (See Table 1.) Other similar ESD-protection devices from TI include the TPD4E1U06, TPD4E1U06, and TPD4E05U06.

Conclusion
ESD-protection diodes that don’t require a $V_{CC}$ connection bring many advantages to the table. No capacitor is needed on the $V_{CC}$ pin to boost the ESD rating; this reduces component count, simplifies layout, and lowers placement cost. Having no $V_{CC}$ connection also guarantees no leakage into the power supply and no ESD damage to any internal nodes that otherwise would be connected to the power supply via $V_{CC}$.

Related Web sites
Interface:
www.ti.com/interface-aaj
www.ti.com/tpd2e001-aaj
www.ti.com/tpd2e2u06-aaj
www.ti.com/tpd4e001-aaj
www.ti.com/tpd4e05u06-aaj
www.ti.com/tpd4e1u06-aaj
For more information about TI’s new-generation ESD-protection devices:
www.ti.com/esd-aaj
Subscribe to the AJ:
www.ti.com/subscribe-aaj

Table 1. Specifications of TPD2E001 versus TPD2E2U06

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>TPD2E001</th>
<th>TPD2E2U06</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{CC}$ connection</td>
<td>Recommended</td>
<td>Not required</td>
</tr>
<tr>
<td>Contact ESD (kV)</td>
<td>±8</td>
<td>±25</td>
</tr>
<tr>
<td>Air ESD (kV)</td>
<td>±15</td>
<td>±30</td>
</tr>
<tr>
<td>$C_{IN}$ (pF)*</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Clamping voltage (V)**</td>
<td>12</td>
<td>9.5</td>
</tr>
</tbody>
</table>

* Capacitance measured at f = 1 MHz, $V_{BIAS} = 2.5$ V.
** Clamping voltage measured using TLP curve at 1 A, 100-ns pulse width.
TI Worldwide Technical Support

Internet
TI Semiconductor Product Information Center
Home Page
support.ti.com

TI E2E™ Community Home Page
e2e.ti.com

Product Information Centers

<table>
<thead>
<tr>
<th>Region</th>
<th>Phone</th>
<th>Fax</th>
<th>Internet/Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americas</td>
<td>+1(512) 434-1560</td>
<td></td>
<td>support.ti.com/sc/pic/americas.htm</td>
</tr>
<tr>
<td>Brazil</td>
<td>0800-891-2616</td>
<td>+1(972) 927-6377</td>
<td>support.ti.com/sc/pic/americas.htm</td>
</tr>
<tr>
<td>Mexico</td>
<td>0800-670-7544</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Europe, Middle East, and Africa

Phone
- European Free Call: 00800-ASK-TEXAS (00800 275 83927)
- International: +49 (0) 8161 80 2121
- Russian Support: +7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax: +(49) (0) 8161 80 2045
Internet: www.ti.com/asktexas
Direct Email: asktexas@ti.com

Asia

<table>
<thead>
<tr>
<th>Region</th>
<th>Phone</th>
<th>Toll-Free Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td>1-800-999-084</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>800-820-8682</td>
</tr>
<tr>
<td>Hong Kong</td>
<td></td>
<td>800-96-5941</td>
</tr>
<tr>
<td>India</td>
<td></td>
<td>000-800-100-8888</td>
</tr>
<tr>
<td>Indonesia</td>
<td></td>
<td>001-803-8861-1006</td>
</tr>
<tr>
<td>Korea</td>
<td></td>
<td>080-551-2804</td>
</tr>
<tr>
<td>Malaysia</td>
<td></td>
<td>1-800-80-3973</td>
</tr>
<tr>
<td>New Zealand</td>
<td></td>
<td>0800-446-934</td>
</tr>
<tr>
<td>Philippines</td>
<td></td>
<td>1-800-765-7404</td>
</tr>
<tr>
<td>Singapore</td>
<td></td>
<td>800-886-1028</td>
</tr>
<tr>
<td>Taiwan</td>
<td></td>
<td>0800-006800</td>
</tr>
<tr>
<td>Thailand</td>
<td></td>
<td>001-800-886-0010</td>
</tr>
<tr>
<td>International: 86-21-23073444</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fax: 86-21-23073686
Email: tiasia@ti.com or ti-china@ti.com
Internet: support.ti.com/sc/pic/asia.htm

Important Notice: The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI's standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer’s applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company’s products or services does not constitute TI’s approval, warranty or endorsement thereof.

© 2014 Texas Instruments Incorporated

E2E is a trademark of Texas Instruments. All other trademarks are the property of their respective owners.
Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products
Audio www.ti.com/audio
Amplifiers amplifier.ti.com
Data Converters dataconverter.ti.com
DLP® Products www.dlp.com
DSP dsp.ti.com
Clocks and Timers www.ti.com/clocks
Interface interface.ti.com
Logic logic.ti.com
Power Mgmt power.ti.com
Microcontrollers microcontroller.ti.com
RFID www.ti-rfid.com
OMAP Applications Processors www.ti.com/omap
Wireless Connectivity www.ti.com/wirelessconnectivity

Applications
Automotive and Transportation www.ti.com/automotive
Communications and Telecom www.ti.com/communications
Computers and Peripherals www.ti.com/computers
Consumer Electronics www.ti.com/consumer-apps
Energy and Lighting www.ti.com/energy
Industrial www.ti.com/industrial
Medical www.ti.com/medical
Security www.ti.com/security
Space, Avionics and Defense www.ti.com/space-avionics-defense
Video and Imaging www.ti.com/video

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2014, Texas Instruments Incorporated