Dependences of Damping Frequency and Damping Factor of Bi-Polar Trigger Waveforms on Transient-Induced Latchup

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Abstract − The dependences of damping frequency and damping factor of bi-polar trigger waveforms on transient-induced latchup (TLU) were characterized by device simulation and verified by experimental measurement. From the simulation results, the bi-polar trigger waveform with damping frequency of several tens of megahertz can trigger on TLU most easily. But, TLU is less sensitive to bi-polar trigger waveforms with an excessively large damping factor, an excessively high damping frequency, or an excessively low damping frequency. The simulation results have been experimentally verified with the silicon controlled rectifier (SCR) test structures fabricated in a 0.25-μm CMOS technology.

I. Introduction

Recently, transient-induced latchup (TLU) has attracted much more reliability attentions than before in CMOS technology [1]-[8]. This tendency results from not only the progress of the more integrated functionality into a single chip, but also the strict requirements of reliability test standards such as system-level electrostatic discharge (ESD) test [9] for electromagnetic compatibility (EMC) regulation. Under such a system-level ESD test, it has been proved that the bi-polar (underdamped sinusoidal) voltage on power or ground lines (pins) of CMOS ICs can easily trigger on TLU [10], even though such TLU-sensitive CMOS ICs have already met the requirements of the quasi-static latchup test standard [11].

TLU immunity of CMOS ICs is strongly dependent on the related dominant parameters of the bi-polar trigger voltage such as voltage amplitude, damping frequency, and damping factor. In real situations, all these parameters depend on the charged voltage of ESD gun, the adopted TLU test mode, and the resonance network where the device under test (DUT) located, etc. The board-level transient voltage coupled into chips will strongly depend on the parasitic capacitance, inductance, and resistance of metal traces in board-level and chip-level layout. Furthermore, some of board-level noise decoupling filters are often used to reduce the transient voltage into chips. Therefore, the damping frequency and damping factor of the bi-polar trigger waveforms reaching to the chips will be different in each case. However, so far it hasn't been investigated yet how these parameters will affect the TLU immunity of the DUT.

In this work, the dependences of both damping frequency and damping factor of bi-polar trigger waveforms on transient-induced latchup are investigated with device simulation and silicon verification.

II. Test Structure and Test Method

An SCR structure is used as the test structure for TLU measurements because the occurrence of latchup results from the parasitic SCR in CMOS ICs. The device cross-sectional view and layout top view of the SCR structure are sketched in Figs. 1(a) and 1(b), respectively. The geometrical parameters such as D, S, and W represent the distances between well-edge and well (substrate) contact, anode and cathode, and the adjacent contacts, respectively. All the SCR structures are fabricated in a 0.25-μm salicided CMOS technology.

To practically demonstrate the occurrence of TLU, a component-level TLU measurement setup with bi-polar trigger is used [12], as shown in Fig. 2. Through an optimal design for placing a small current-limiting resistance (5Ω) but removing the current-blocking diode between V_{DD} node and the power supply, this measurement setup can accurately evaluate the TLU immunity of DUT without over estimation [13]. An ESD simulator is used to generate the bi-polar trigger voltage, V_{Charge}. A capacitor with capacitance of 200pF is employed as the charged capacitor. The DUT is the SCR structure shown in Fig. 1. The P^+ anode and the N^+ well contact of SCR are connected together to V_{DD}, whereas the N^+ cathode and the P^+ substrate contact are connected together to ground. I_{DD} is the current flowing into the P^+ anode and the N^+ well contact of SCR.

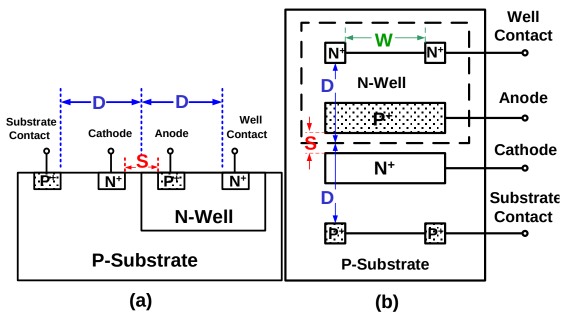

Fig. 1. (a) Device cross-sectional view, and (b) layout top view, of the SCR structure in CMOS process for TLU measurements.

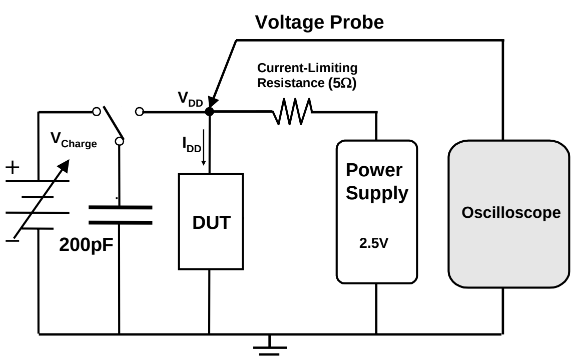

Fig. 2. A component-level TLU measurement setup with bi-polar trigger [12].

With bi-polar trigger sources (V_{Charge}) of +10V and +15V, Figs. 3(a) and 3(b) show the measured V_{DD} and I_{DD} transient responses of SCR, respectively. In Fig. 3(a), with a smaller V_{Charge} of +10V, TLU doesn't occur, and V_{DD} acts as the intended bi-polar voltage just similar to that under the system-level ESD test [14]. In Fig. 3(b), with a larger V_{Charge} of +15V, TLU is triggered on. Thus, I_{DD} will significantly increase up to 120mA, and V_{DD} is pulled down to the latchup holding voltage (~1.5V). Those measured waveforms have demonstrated the occurrence of transient-induced latchup.

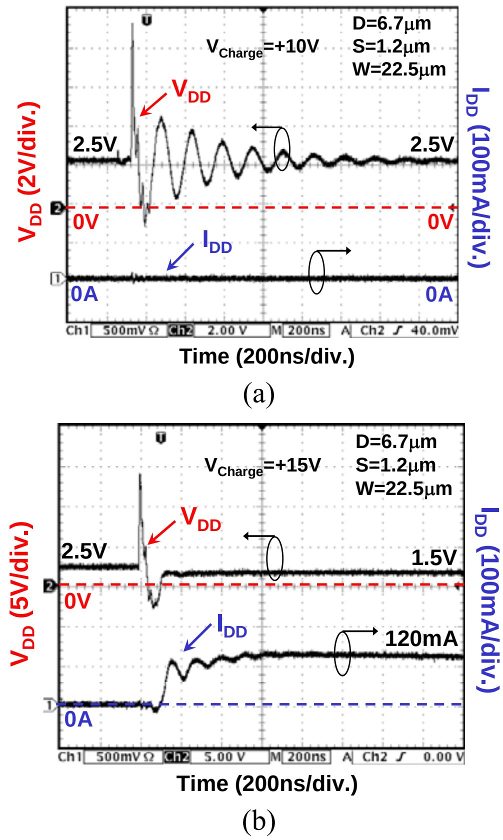

Fig. 3. The measured V_{DD} and I_{DD} transient responses of the SCR with V_{Charge} of (a) +10, and (b) +15V.

III. TLU Simulation

A two-dimensional device simulation tool (MEDICI) is used to characterize the dependences of both damping frequency and damping factor of bi-polar trigger waveforms on TLU. As shown in Fig. 4, a specified SCR structure with geometrical parameters of D=6.7μm and S=1.2μm (the same as that in Fig. 3) is used for all the TLU device simulation in this work. To apply a bi-polar trigger waveform on V_{DD} of the defined SCR structure, a specific time-dependent voltage source function in the following is used

$$V_{DD}(t) = V_0 + V_P \cdot \exp\left(-(t-t_d)D_{Factor}\right) \cdot \sin\left(2\pi D_{Freq}(t-t_d)\right). \quad (1)$$

With the proper parameters such as initial voltage V_0, time delay t_d, applied voltage amplitude V_P, damping factor D_{Factor}, and damping frequency D_{Freq}, an intended bi-polar voltage can be constructed. For simplicity, in this work, both V_0 and t_d are kept at the fixed values of 2.5V and 50ns, respectively. Fig. 5 shows the simulated V_{DD} and I_{DD} transient responses for the bi-polar trigger voltage ($V_{DD}(t)$ in (1)) with D_{Factor}, D_{Freq}, and V_P of $2\times10^7 s^{-1}$, 20MHz, and +14.6V, respectively. Clearly, V_{DD} is the intended positive-going bi-polar voltage. Once TLU is triggered on by the sweep-back current, I_{Sb} [10], caused by the stored minority carriers within SCR, I_{DD} will significantly increase when V_{DD} increases from the negative peak voltage, $-V_{Peak}$, to the normal operating voltage of +2.5V (87.5ns<t<112.5ns, in Fig. 5). Furthermore, I_{DD} is kept at a high current state (150mA) when V_{DD} finally returns to its normal operating voltage of +2.5V.

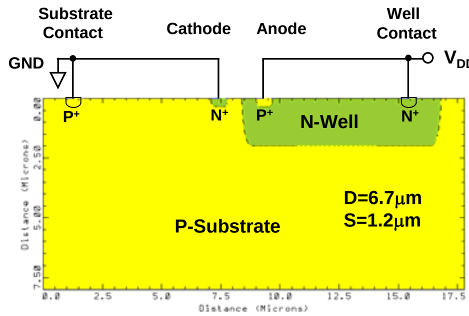

Fig. 4. The SCR structure used in a two-dimensional device simulation tool (MEDICI).

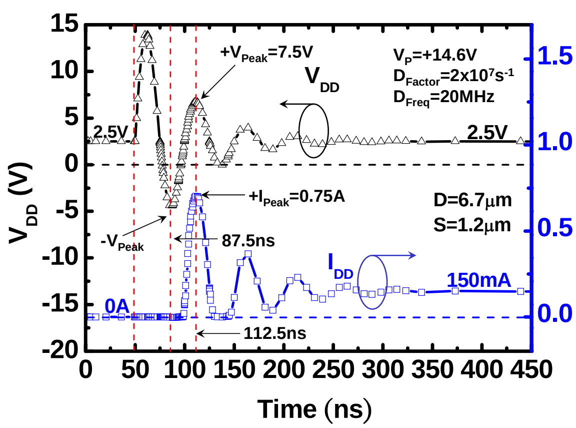

Fig. 5. The simulated V_{DD} and I_{DD} transient responses for bi-polar trigger voltage (V_{DD}) with D_{Factor}, D_{Freq}, and V_P of $2\times10^7s^{-1}$, 20MHz, and +14.6V, respectively. TLU is triggered on by the sweep-back current [10] when V_{DD} increases from $-V_{Peak}$ to the normal operating voltage of +2.5V (87.5ns<t<112.5ns).

Fig. 6 shows the corresponding simulated 2-D current flow lines with respect to various transient timing points. Forward well (substrate) contact current appears when N-well/P-substrate junction is forward-biased (timing points C and D). When V_{DD} increases from $-V_{Peak}$ (timing points C) to the normal operating voltage of +2.5V (timing points E), TLU can be triggered on due to large enough I_{Sb} (timing points E-H). The simulation results in Figs. 5 and 6 are consistent with the experimental verification in Fig. 3. So, the device simulation proposed in this work can be used to investigate the dependences of damping frequency and damping factor of bi-polar trigger waveforms on TLU.

The parameter of $-V_{Peak}$ is an important reference value because it determines how large I_{Sb} will be produced. For V_{DD} at $-V_{Peak}$, the N-well/P-substrate junction of SCR has the largest forward-biased current. Such forward-biased current will result in I_{Sb} to initiate TLU when V_{DD} increases from $-V_{Peak}$ to the normal operating voltage of +2.5V. Larger (i.e. more negative) $-V_{Peak}$ will result in larger I_{Sb}, so that TLU can be triggered on more easily. In addition to the parameter of $-V_{Peak}$, the time period needed for bi-polar trigger voltage increasing from $-V_{Peak}$ to the normal operating voltage (+2.5V) is also an important parameter to determine whether TLU occurs [10]. If such time period is too long, TLU doesn't occur due to insufficient I_{Sb}.

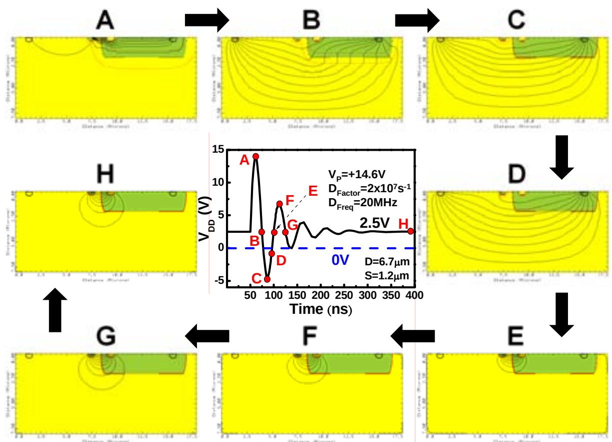

Fig. 6. The simulated 2-D current flow lines with respect to various transient timing points. Here the bi-polar trigger voltage has D_{Factor}, D_{Freq}, and V_P of $2\times10^7s^{-1}$, 20MHz, and +14.6V, respectively.

A. Relations between D_{Factor} and Minimum Positive (Negative) V_P to Initiate TLU

With a fixed D_{Freq} of 8MHz, the relations between D_{Factor} and V_{P+} (V_{P-}) are shown in Fig. 7. V_{P+} (V_{P-}) is defined as the magnitude of minimum positive (negative) V_P to initiate TLU. If the magnitude of the applied positive (negative) V_P is smaller than V_{P+} (V_{P-}), TLU will not be triggered on. The reason is that a too small V_P cannot provide a large enough $-V_{Peak}$ (i.e. large enough I_{Sb}) to initiate TLU. In addition, because D_{Factor} determines how fast the bi-polar trigger voltage will be attenuated in time domain, so $-V_{Peak}$ strongly depends on D_{Factor}. For example, larger D_{Factor} means larger voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. smaller $-V_{Peak}$ or I_{Sb}). Thus, the relations between D_{Factor} and V_{P+} (V_{P-}) are very important for TLU characterization.

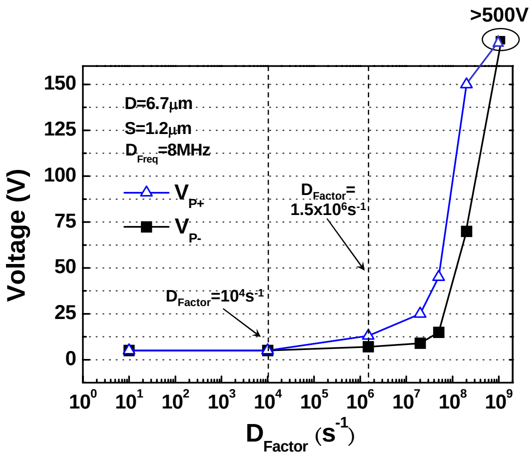

Fig. 7. The relations between D_{Factor} and V_{P+} (V_{P-}). V_{P+} (V_{P-}) is defined as the magnitude of minimum positive (negative) V_P to initiate TLU.

For $D_{Factor}<10^4 s^{-1}$, both V_{P+} and V_{P-} are independent on D_{Factor} and equal to 6V. From (1), for the given D_{Freq} of 8MHz, such small D_{Factor} will not result in an obvious voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. $-V_{Peak}$ isn't obviously attenuated). Thus, for such a low D_{Factor}, if a known minimum $-V_{Peak}$ to initiate TLU of SCR is fixed, both V_{P+} and V_{P-} are the same and independent to D_{Factor}.

For $D_{Factor}>10^4 s^{-1}$, both V_{P+} and V_{P-} increase with D_{Factor}. The reason is that a larger D_{Factor} will result in a larger voltage attenuation (i.e. smaller $-V_{Peak}$) within the first cycle of the bi-polar trigger waveform, so a larger V_{P+} (V_{P-}) is necessary for a higher D_{Factor} to provide a known fixed $-V_{Peak}$ (i.e. known fixed I_{Sb}) which can initiate TLU. In addition, with a given D_{Factor}, V_{P+} is larger than V_{P-}. Compared with the negative-going ($V_P<0$) bi-polar voltage, the positive-going ($V_P>0$) bi-polar voltage needs to take additional half duration for decaying before it reaches to $-V_{Peak}$. As a result, V_{P+} larger than V_{P-} is necessary to compensate the additional voltage attenuation within the half duration if the minimum $-V_{Peak}$ to initiate TLU is fixed.

B. Relations between D_{Freq} and Minimum Positive (Negative) V_P to Initiate TLU

With a fixed D_{Factor} of $1.5\times10^6 s^{-1}$, the relations between D_{Freq} and V_{P+} (V_{P-}) are shown in Fig. 8. D_{Freq} is inverse proportional to the duration of bi-polar trigger waveform. Thus, D_{Freq} determines how fast the bi-polar trigger waveform will be attenuated within its first duration (cycle). For example, for a fixed V_P and D_{Factor}, larger D_{Freq} (shorter duration) means that bi-polar trigger voltage takes less time for decaying before reaching to $-V_{Peak}$ (i.e. larger $-V_{Peak}$). That is, $-V_{Peak}$ (I_{Sb}) also strongly depends on D_{Freq}, so the relations between D_{Freq} and V_{P+} (V_{P-}) are significant for TLU characterization.

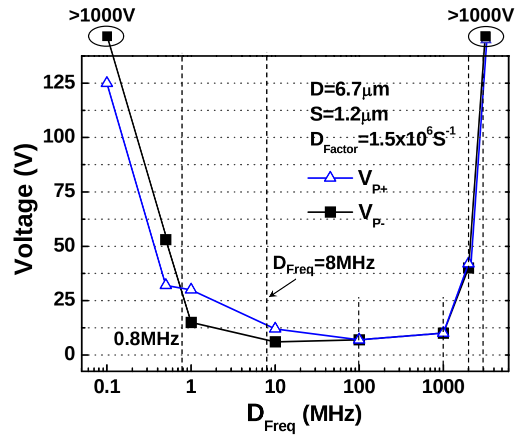

Fig. 8. The relations between D_{Freq} and V_{P+} (V_{P-}). V_{P+} (V_{P-}) is defined as the magnitude of minimum positive (negative) V_P to initiate TLU.

For $0.8\text{MHz}<D_{Freq}<100\text{MHz}$, V_{P+} is larger than V_{P-} because the positive-going bi-polar voltage takes additional half duration for decaying before it reaches to $-V_{Peak}$. Thus, V_{P+} larger than V_{P-} is needed to compensate the additional voltage attenuation within the half duration if the minimum $-V_{Peak}$ to initiate TLU is fixed.

For $D_{Freq}<0.8\text{MHz}$, however, V_{P+} is smaller than V_{P-}. For V_{P-} case, Fig. 9 shows the simulated V_{DD} and I_{DD} transient responses for bi-polar trigger voltage with D_{Factor}, D_{Freq}, and V_P of $1.5\times10^6 s^{-1}$, 0.1MHz, and -200V, respectively. Clearly, the given D_{Factor} of $1.5\times10^6 s^{-1}$ is too large for such a low-frequency bi-polar trigger to perform a negative-going bipolar voltage, but a negative-going uni-polar overdamped voltage instead. TLU doesn't occur because the time period needed for V_{DD} increasing from $-V_{Peak}$ to the normal operating voltage (+2.5V) is too long (~3μs) to generate sufficient I_{Sb} [10], even though the magnitude of $-V_{Peak}$ is as high as 28V. Thus, I_{DD} is negligible after V_{DD} finally returns to its normal operating voltage (+2.5V). For V_{P+} case, Fig. 10 shows the simulated V_{DD} and I_{DD} transient responses for bi-polar trigger with the same parameters as those used in Fig. 9 but with V_P of +150V. Similarly, the given D_{Factor} of $1.5\times10^6 s^{-1}$ is too large for such a low-frequency V_{DD} to perform a positive-going bipolar voltage, but a positive-going uni-polar overdamped voltage instead.

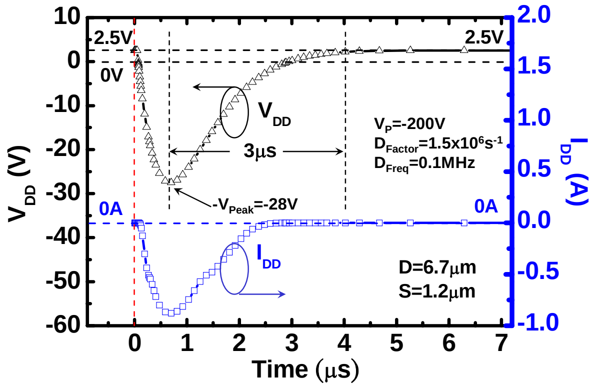

Fig. 9. The simulated V_{DD} and I_{DD} transient responses for bi-polar trigger voltage with D_{Factor}, D_{Freq}, and V_P of $1.5\times10^6 s^{-1}$, 0.1MHz, and -200V, respectively. TLU doesn't occur because the time period needed for V_{DD} increasing from -V_{Peak} to the normal operating voltage (+2.5V) is too long (~3μs) to generate sufficient I_{Sb} [10].

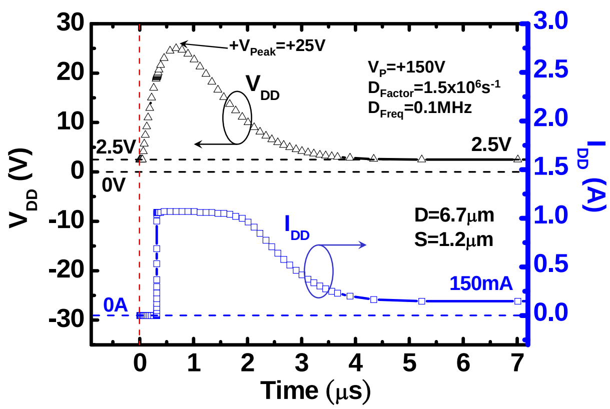

Fig. 10. The simulated V_{DD} and I_{DD} transient responses for bi-polar trigger voltage with the same parameters as those used in Fig. 9 but with V_P of +150V. TLU can be triggered on by the transient displacement current while V_{DD} initially increases from the normal operating voltage (+2.5V) to +V_{Peak}.

However, TLU can be triggered on by the transient displacement current while V_{DD} initially increases from the normal operating voltage (+2.5V) to +V_{Peak}, even though the magnitudes of both V_P and +V_{Peak} (150V and 25V) are lower than those (200V and 28V) in Fig. 9. Once TLU is triggered on, I_{DD} will significantly increase with V_{DD}, and finally is kept at a high current state (150mA) when V_{DD} finally returns to the normal operating voltage (+2.5V). Thus, from the simulation results in Figs. 9 and 10, it can be founded out that the positive-going uni-polar trigger can initiate TLU more easily than negative-going uni-polar trigger if the time period needed for negative-going uni-polar trigger increasing from -V_{Peak} to the normal operating voltage (+2.5V) is too long (~3μs in Fig. 9).

For D_{Freq}>100MHz, both V_{P+} and V_{P-} are almost the same because the given D_{Factor} of $1.5\times10^6 s^{-1}$ is too small to produce an apparent voltage attenuation of such a high-frequency bi-polar trigger within its first duration (i.e. -V_{Peak} isn't obviously attenuated). Thus, if a known minimum -V_{Peak} to initiate TLU of SCR is fixed, both V_{P+} and V_{P-} will be almost the same. In addition, for D_{Freq}>1000MHz, both V_{P+} and V_{P-} significantly increase, as shown in Fig. 8. Fig. 11 shows the simulated V_{DD} and I_{DD} transient responses for bi-polar trigger with D_{Factor}, D_{Freq}, and V_P of $1.5\times10^6 s^{-1}$, 2GHz, and -60V, respectively. Clearly, +I_{Peak} doesn't appear at +V_{Peak} but at the end of the first duration (~50.5ns). That is, I_{DD} cannot follow the V_{DD} variation in time for such a high-D_{Freq} (>1GHz) bi-polar trigger waveform. Thus, +I_{Peak} of 0.3A is lower than that (0.75A) for low-D_{Freq} (20MHz) case in Fig. 5, even though +V_{Peak} of +60V is much larger than that (+7.5V) in Fig. 5. This means that the higher V_{P+} or V_{P-} is necessary for such a high-D_{Freq} (>1GHz) bi-polar trigger waveform to provide a fixed I_{Sb} which can initiate TLU, so both V_{P+} and V_{P-} will increase for D_{Freq}>1GHz. If D_{Freq} further increases to above 3GHz, TLU doesn't occur (both V_{P+} and V_{P-} larger than 1000V). The reason is that the duration of bi-polar trigger isn't long enough to sustain a positive-feedback latchup event.

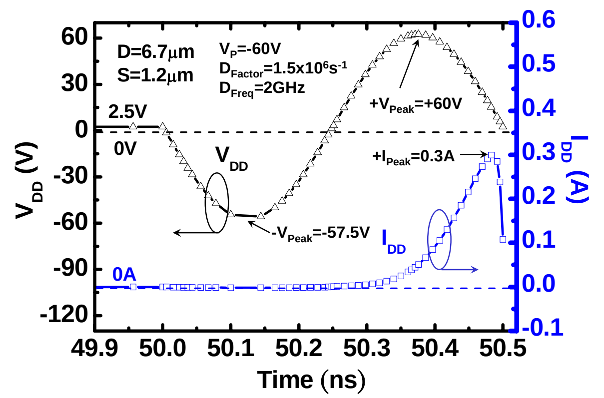

Fig. 11. The simulated V_{DD} and I_{DD} transient responses for bi-polar trigger voltage with D_{Factor}, D_{Freq}, and V_P of $1.5\times10^6 s^{-1}$, 2GHz, and -60V, respectively. I_{DD} cannot follow the V_{DD} variation in time for such a high-D_{Freq} (>1GHz) bi-polar trigger waveform, because +I_{Peak} doesn't appear at +V_{Peak} but at the end of the first duration (~50.5ns).

C. Relations between D_{Factor} and Minimum D_{Freq} to Initiate TLU

With a fixed V_P of both +15V and -15V, the relations between D_{Factor} and $D_{Freq(min)}$ are shown in Fig. 12. $D_{Freq(min)}$ is defined as the minimum D_{Freq} to initiate TLU. If the D_{Freq} of bi-polar trigger waveform is lower than $D_{Freq(min)}$, TLU will not be triggered on due to an insufficient I_{Sb} because of the following two reasons. First, a too low D_{Freq} will result in a too long duration of the bi-polar trigger waveform. For a large D_{Factor}, such long duration will lead a serious voltage attenuation within the first cycle of the bi-polar trigger waveform, so there is no large enough $-V_{Peak}$ to provide sufficient I_{Sb} to initiate TLU. Second, for a small D_{Factor}, although there is no serious voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. $-V_{Peak}$ will not be serious attenuated), TLU doesn't occur. The reason is that the time period needed for V_{DD} increasing from $-V_{Peak}$ to the normal operating voltage (+2.5V) is too long to provide sufficient I_{Sb} [10] for initiating TLU. Therefore, the occurrence of TLU is dominated by D_{Freq} and D_{Factor}.

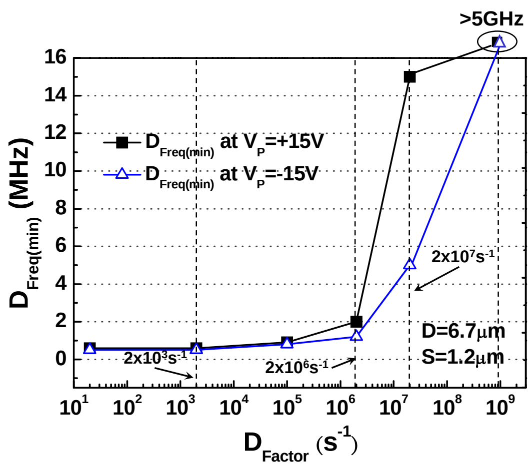

Fig. 12. The relations between D_{Factor} and $D_{Freq(min)}$. $D_{Freq(min)}$ is defined as the minimum D_{Freq} to initiate TLU under a fixed V_P of +15V or -15V.

For $D_{Factor}<2\times10^3 s^{-1}$, $D_{Freq(min)}$ is independent on D_{Factor} and equal to 500kHz. For such a small D_{Factor}, there is no obvious voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. $-V_{Peak}$ will not be serious attenuated). Thus, for a given V_P, the occurrence of TLU is dominated by the time period needed for V_{DD} increasing from $-V_{Peak}$ to the normal operating voltage (+2.5V), i.e. the $D_{Freq(min)}$ of 500kHz, but not dominated by the $-V_{Peak}$ which is a function of D_{Factor}. As a result, for a low D_{Factor} ($<1\times10^5 s^{-1}$), $D_{Freq(min)}$ is independent to D_{Factor}. In addition, for the given V_P of +15V or -15V, $D_{Freq(min)}$ are the same due to the equal $-V_{Peak}$, because no obvious voltage attenuation within the first cycle of the bi-polar trigger waveform for such a small D_{Factor}.

For $D_{Factor}>2\times10^3 s^{-1}$, however, $D_{Freq(min)}$ increases with D_{Factor}. Such a larger D_{Factor} will result in a larger voltage attenuation (i.e. smaller $-V_{Peak}$) within the first cycle of the bi-polar trigger waveform. Thus, for a given V_P, the occurrence of TLU is dominated by the $-V_{Peak}$ which is a function of D_{Factor}, but not dominated by the time period needed for V_{DD} increasing from $-V_{Peak}$ to the normal operating voltage (+2.5V), i.e. the $D_{Freq(min)}$ of 500kHz. In order to provide a known fixed $-V_{Peak}$ to initiate TLU, a higher $D_{Freq(min)}$ (shorter duration) is necessary for a larger-D_{Factor} bi-polar trigger waveform to compensate a larger voltage attenuation. In addition, with V_P of +15V, $D_{Freq(min)}$ is higher than that with V_P of -15V. Compared with the negative-going bi-polar trigger waveform (V_P of -15V), the positive-going bi-polar trigger waveform (V_P of +15V) has a smaller $-V_{Peak}$ because it must take an additional half duration for decaying before it reaches to $-V_{Peak}$. Thus, a higher $D_{Freq(min)}$ is necessary for positive-going bi-polar voltage to compensate an additional voltage attenuation within the half duration of the bi-polar trigger voltage if the minimum $-V_{Peak}$ to initiate TLU is fixed.

D. Relations between D_{Factor} and Maximum D_{Freq} to Initiate TLU

With a fixed V_P of both +15V and -15V, the relations between D_{Factor} and $D_{Freq(max)}$ are shown in Fig. 13. $D_{Freq(max)}$ is defined as the maximum D_{Freq} to initiate TLU. If the D_{Freq} of bi-polar trigger waveform is higher than $D_{Freq(max)}$, TLU will not be triggered on due to the following two reasons. First, for a small D_{Factor}, although there is no serious voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. $-V_{Peak}$ will not be serious attenuated), TLU doesn't occur. I_{DD} cannot follow the V_{DD} variation in time for a high-D_{Freq} bi-polar trigger waveform, so the duration of such a high-D_{Freq} bi-polar trigger waveform is not long enough to sustain the positive-

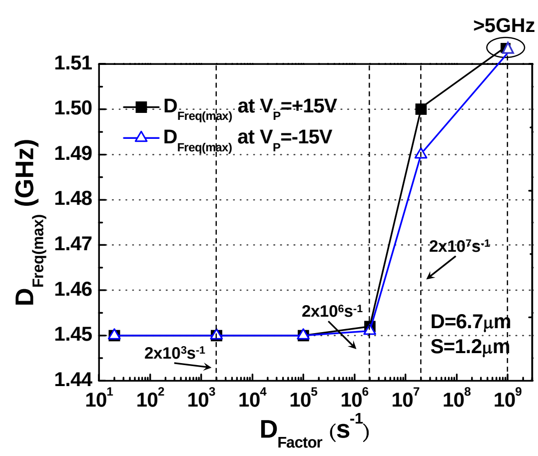

Fig. 13. The relations between D_{Factor} and $D_{Freq(max)}$. $D_{Freq(max)}$ is defined as the maximum D_{Freq} to initiate TLU under a fixed V_P of +15V or -15V.

feedback latchup event. That is, the occurrence of TLU is dominated by D_{Freq}. Second, for an excessively large D_{Factor}, there is still a voltage attenuation within the first cycle of the high-D_{Freq} bi-polar trigger waveform, so there is no large enough $-V_{Peak}$ to provide sufficient I_{Sb} to initiate TLU.

For $D_{Factor}<1\times10^5 s^{-1}$, $D_{Freq(max)}$ is independent to D_{Factor} and equal to 1.45GHz in Fig. 13. For such a small D_{Factor}, there is no obvious voltage attenuation within the first cycle of the bi-polar trigger waveform (i.e. $-V_{Peak}$ will not be serious attenuated). Thus, for a given V_P, the occurrence of TLU is dominated by the time period needed to sustain a positive-feedback latchup event, i.e. the $D_{Freq(max)}$ of 1.45GHz, but not dominated by the $-V_{Peak}$ which is a function of D_{Factor}. As a result, for a low D_{Factor} ($<1\times10^5 s^{-1}$), $D_{Freq(max)}$ is independent to D_{Factor}. In addition, for the given V_P of +15V or -15V, $D_{Freq(max)}$ are the same due to the equal $-V_{Peak}$, because no obvious voltage attenuation within the first cycle of the bi-polar trigger waveform for such a small D_{Factor}.

For $D_{Factor}>1\times10^5 s^{-1}$, however, $D_{Freq(max)}$ increases with D_{Factor} due to a larger voltage attenuation (i.e. smaller $-V_{Peak}$) within the first cycle of the bi-polar trigger waveform. Thus, for a given V_P, the occurrence of TLU is dominated by the $-V_{Peak}$ which is a function of D_{Factor}, but not dominated by the time period needed to sustain a positive-feedback latchup event, i.e. the $D_{Freq(max)}$ of 1.45GHz. In order to provide a known fixed $-V_{Peak}$ to initiate TLU, a higher $D_{Freq(max)}$ (shorter duration) is necessary for a larger-D_{Factor} bi-polar trigger to compensate a larger voltage attenuation. In addition, with V_P of +15V, $D_{Freq(max)}$ is higher than that with V_P of -15V. The reason is that a higher $D_{Freq(max)}$ is necessary to compensate an additional voltage attenuation because the positive-going bi-polar voltage takes additional half duration for decaying before it reaches to $-V_{Peak}$.

From above comprehensive simulation results, it's useful to qualitatively evaluate an optimal bi-polar trigger source which can efficiently evaluate the TLU immunity of CMOS ICs without over estimation. In Fig. 8, it can be founded out that the bi-polar trigger waveform with D_{Freq} of several tens of megahertz can initiate TLU most easily, because there is a lowest V_{P+} (V_{P-}) (i.e. most sensitive to TLU) of SCR for $10MHz<D_{Freq}<100MHz$. Otherwise, TLU is less sensitive to bi-polar trigger waveforms with an excessively large D_{Factor} (Fig. 7), an excessively high D_{Freq} (Fig. 8), or an excessively low D_{Freq} (Fig. 8). In addition, the relations among D_{Factor}, $D_{Freq(min)}$, $D_{Freq(max)}$ also provide the useful information for characterizing bi-polar trigger waveform to initiate TLU.

IV. Experimental Verification

The simulation results in this work can be experimentally verified with the TLU measurement setup in Fig. 2. Figs. 14 and 15 show the TLU levels of the fabricated SCR devices with various geometrical parameters. The TLU level is defined as the minimum positive (negative) V_{Charge} which can trigger on TLU. The magnitudes of the negative TLU level (<9V) of all the SCR structures are smaller than that of the positive TLU level (>13V) unless the SCR is latchup-free (i.e. latchup holdinging voltage is larger than +2.5V). With the measured bi-polar trigger waveform in Fig. 3(a), D_{Freq} is about 8MHz (duration is about 125ns) and D_{Factor} is about $1.5\times10^6 s^{-1}$ (estimation from (1)). From the simulation results in

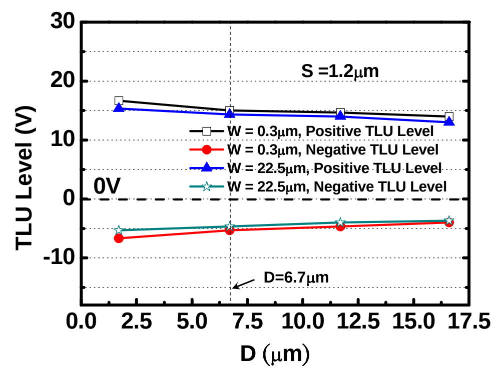

Fig. 14. The measured TLU level of the SCR with various D and W but a fixed S of 1.2μm. The magnitudes of the negative TLU level (<9V) of all the SCR structures are smaller than that of the positive TLU level (>13V).

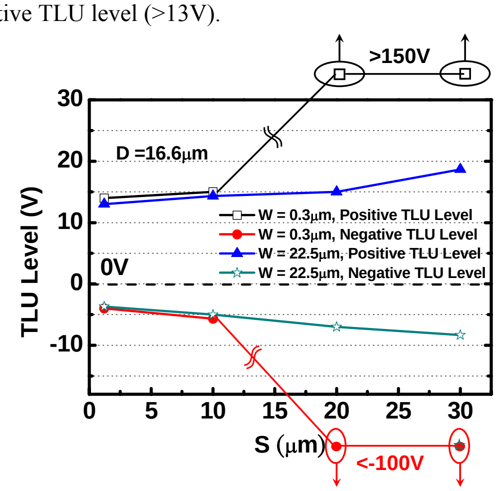

Fig. 15. The measured TLU level of the SCR with various S and W but a fixed D of 16.6μm. The magnitudes of the negative TLU level (<9V) of all the SCR structures are smaller than that of the positive TLU level (>13V) unless the SCR is latchup-free.

Figs. 7 and 8, V_{P-} is smaller than V_{P+} for bi-polar trigger voltage with D_{Freq} of 8MHz and D_{Factor} of $1.5\times10^6 s^{-1}$. The experimental verifications in Figs. 14 and 15 are consistent with the device simulation results in Figs. 7 and 8.

V. Conclusion

The dependences of damping frequency and damping factor of bi-polar trigger waveforms on transient-induced latchup have been characterized with device simulation and experimental verification. From the simulation results, the bi-polar trigger waveform with D_{Freq} of several tens of megahertz can initiate TLU most easily. TLU is less sensitive to bi-polar trigger waveforms with an excessively large D_{Factor}, an excessively high D_{Freq}, or an excessively low D_{Freq}. Thus, it's useful to qualitatively evaluate an optimal bi-polar trigger source which can efficiently evaluate the TLU immunity of CMOS ICs without over estimation. The simulation results analyzed in this work have been practically verified with the SCR test structures fabricated in a 0.25-μm CMOS technology.

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