Metastability in Lattice Devices

March 2004 Technical Note TN1055

Introduction

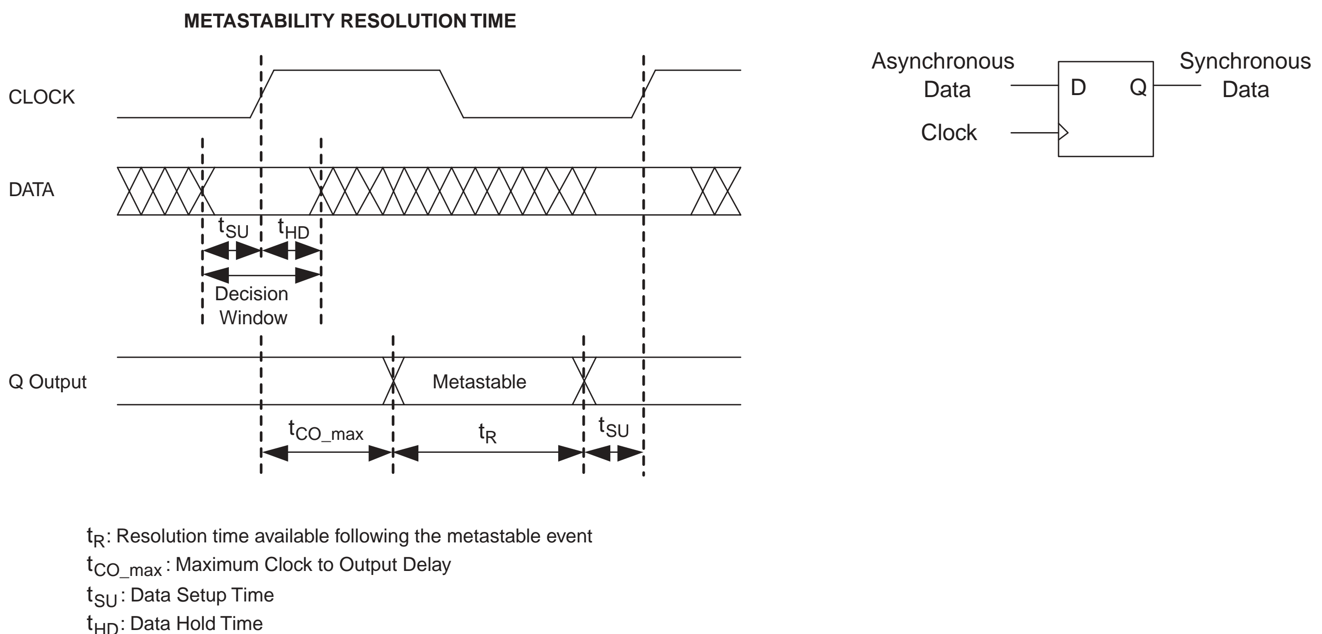
There are two critical issues in metastability characterization. One is to devise an accurate but practical measurement technique and the other is a basic knowledge of metastability. The measurement procedure requires a comprehensive knowledge of metastability.

In actual applications, the user may deviate from meeting the ideal register setup and hold times. When the data and clock do not satisfy the setup and hold times, the logic state of the flip-flop becomes unpredictable. One measurable symptom of the problem is increased clock-to-out time. The susceptibility of a circuit to reach this metastable state can be described using a probabilistic equation. This technical note describes the basics of metastability, and the measurement methods and equations necessary to arrive at the device characteristics for Lattice Programmable Logic Devices (PLDs). A sample device from each PLD family is used to summarize the data. It is assumed that the devices within each family have similar characteristics.

Basics of Metastability

Refer to the single-stage D Flip-Flop shown in Figure 1.

Figure 1. Single-Stage Synchronizer



Minimum data set-up (t_{SU}) and hold (t_{HD}) times must be met for the register to output synchronized data.

The data input to the D flip-flop is asynchronous to the clock. The arrival time of the input data relative to the clock is not known and a "danger zone" is created. The transition of the correct input data could enter the Decision Window as illustrated in Figure 1.

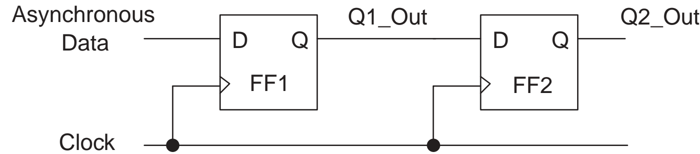
After a clock-to-output delay (t_{CO}), the input data appears at the Q output. If the input data enters the "danger zone", the Q output is likely to be in a metastable state until the internal silicon settles to either a logic high or low. The extra time required to resolve the logic state is called resolution time (t_R) and the Decision Window is represented by a Metastability Window (W).

Solution to Metastability

Two flip-flops in a series is the best known and easiest solution to avoid metastability.

The resolution time varies exponentially with the size of the Metastability Window. In other words, if the data barely missed the set-up/hold time requirement, the flip-flop decision will take slightly longer than the t_{CO}. When the data arrives in the middle of the Metastability Window, the resolution time will be much longer.

Figure 2. Two Flip-Flop Solution



When an input data transition falls within the Metastability Window of the FF1, it causes a longer resolution time at the output of FF1 Q1_Out.

When the resolved Q1_Out arrives at FF2, the probability that the signal transition will fall on top of the Metastability Window FF2 data input is very low. In a practical circuit, cascading two flip-flops essentially squares the probability of failure.

Measurement Method

Devising reliable and repeatable measurement methods is challenging. A wealth of information has been published about metastability characterization but all of these techniques have proven difficult to recreate reliably.

A report by Foley[1] describes a measurement technique that is reliable and repeatable. The measured data resolution is as accurate as the test equipment resolution. The data used in this technical note is derived using Foley's technique. This method does not require additional external active circuitry other than the test equipment.

Derivation of Equations

t_R: Available Resolve Time

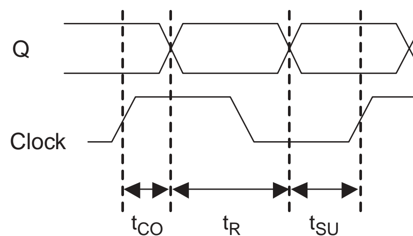
Assume that the Q output will be sampled on the next clock event, the Q output must be resolved prior to the next clock by the set-up time. The maximum available resolution time t_R at the given clock frequency, f_C, is:

$$t_R = (1/ f_C - t_{CO} - t_{SU}) \tag{1}$$

where: f_C = Clock frequency
t_{CO} = Maximum clock-to-output delay
t_{SU} = Minimum set-up time

The t_R shown in Figure 3 is the time where the Q output is given to recover to a legal logic level after t_{CO} and before the set-up time of the next clock.

Figure 3. Available Resolution Time



τ: Resolving Time Constant

The Resolving Time Constant, τ, comes from the expression that describes the probability of a metastable event lasting longer than some time, t. This probability is expressed as:

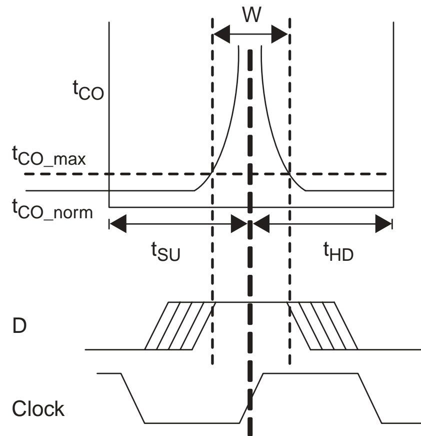
$$P = e^{-t/\tau} \quad (2)$$

The method uses a stable synchronous source for the measurement. The set-up and hold times of the input data relative to the clock can be adjusted while observing the Q output for the metastable event. The Q output appears to have equally distributed high and low logic levels.

W: Metastability Window

The Metastability Window, W, can be determined by accurately measuring the Clock-To-Output Propagation Delay Time (t_{CO}) with variation in the Set-up (t_{SU}) and Hold (t_{HD}) times. Figure 4 shows the t_{CO} versus t_{SU}/t_{HD} curves. When the Set-up time or Hold time is violated, the Clock-To-Output Delay is increased. The t_{CO_MAX} is specified in the device data sheet. When the t_{CO} is measured longer than the t_{CO_MAX}, the device is considered to be in the metastable state.

Figure 4. Metastability Window



Assume the data arrives uniformly over clock cycle T. The probability that data will arrive in W in a clock period T is

$$P = W/T = W * f_C \quad (3)$$

where: W = Metastability window
f_C = Clock frequency

If the data rate is f_D, then the data will arrive at data rate f_D. The rate of metastability becomes:

$$R = W * f_C * f_D \quad (4)$$

where f_D is data rate.

The probability of a metastable event lasting longer than some time, t_R, is from Equation 1,

$$P = e^{-tr/\tau} = 1/(e^{tr/\tau}) \quad (5)$$

Failure rate = Metastability Rate * Probability of Metastability.

$$= W * Fc * Fd * e^{-tr/\tau} \quad (6)$$

Mean Time Between Failures (MTBF)

The Metastability Failure Rate may be defined as the susceptibility of a flip-flop to reach the metastable state at a designated time following the clock. The phrase “at a designated time following the clock” is the key to understanding the data correctly. This failure rate is often converted to Mean Time Between Failure (MTBF).

MTBF = 1 / Metastability Failure Rate

$$MTBF = 1/\ Failure\ Rate = 1/\ (W * f_C * f_D * e^{-tr/\tau}) = e^{tr/\tau}/\ (W * f_C * f_D) \quad (7)$$

where: f_D = Clock frequency
f_D* = Data rate (not data frequency)
W = Metastability window
t_R = Resolve time available
τ = Resolving time constant

Note: If f_D is measured by a frequency meter, the data changes twice per cycle. In this case, f_D must be replaced by 2 * f_D in the above equation.

The graphical representation of the data has been represented in a semi-log graph.

Converting the exponential expression to decades form,

$$e^{tr/\tau} = 10^{tr/\tau\delta} \quad (8)$$

where: $\tau\delta = \tau / \log(e)$

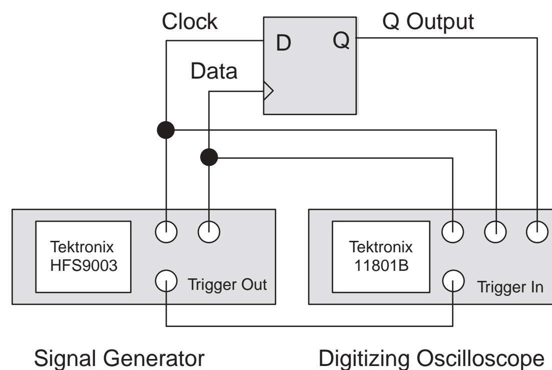
Equation 7 becomes:

$$MTBF = 10^{tr/\tau\delta} / (W * Fc * Fd) \quad (9)$$

Test Set-up

Using the signal generator shown in Figure 5, the set-up and hold time are varied relative to the clock. The scope displays the Q output waveform while adjusting the data and clock relative timing. The Metastability Window starts when the data enters the Metastable Window and ends as the data escapes the Metastable Window. The resolution of the signal generator is the only sizable limitation of the accuracy of the measurement. In practice, the limitation does not count as much as the importance of the accuracy of the data. After the Metastability Window is measured, the data timing is set to the center of the window to observe the decay function resolution time, t_R.

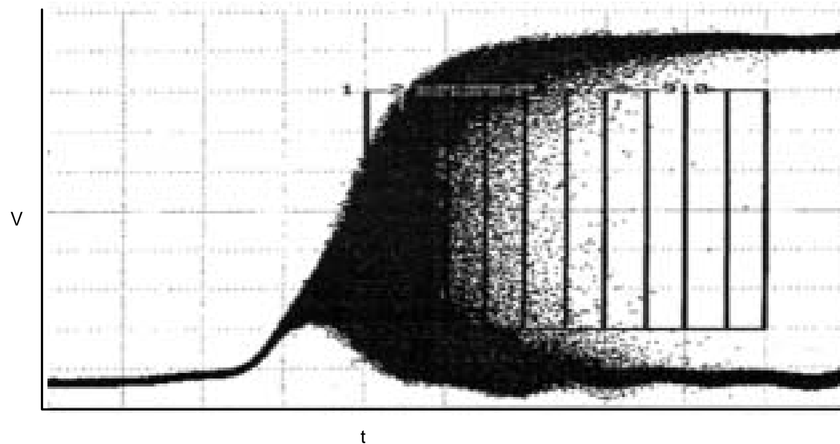
Figure 5. Test Set-up



Mask Counting

The logic level plots accumulated in the scope screen are shown in Figure 6. The decay of this metastable behavior over time is observed as expected.

Figure 6. Masks Used in Overlaid Q Output



The 11801B digital oscilloscope is used for the event counter by zones (masks). The top and bottom of each mask is set to V_{OH_MIN} and V_{OL_MAX} of the device, respectively. The width of each mask represents a time unit for comparing events at different times. The tallies of these masks reveal the population decay rate as expressed in Equation 2. The number of masks should be chosen so that enough decay rate is observed.

Table 1 represents the actual measurements taken for an ispMACH™ 4000 device. Eight masks are used. The population column numbers are actual illegal event counts.

Table 1. Example of Data

Mask	Population
1	5.10E+03
2	2.66E+03
3	1.21E+03
4	4.50E+02
5	1.29E+02
6	3.20E+01
7	9.00E+00
8	4.00E+00

Exponential Decay of Failure

Figure 7. Exponential Decay of Failure

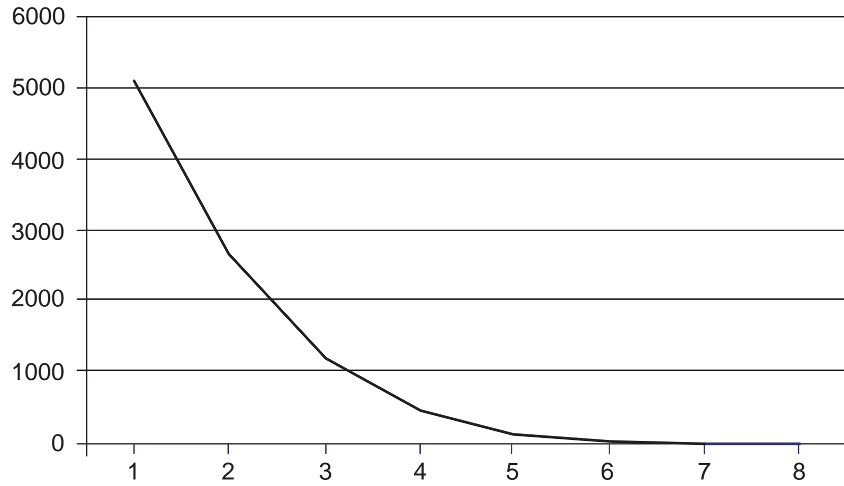
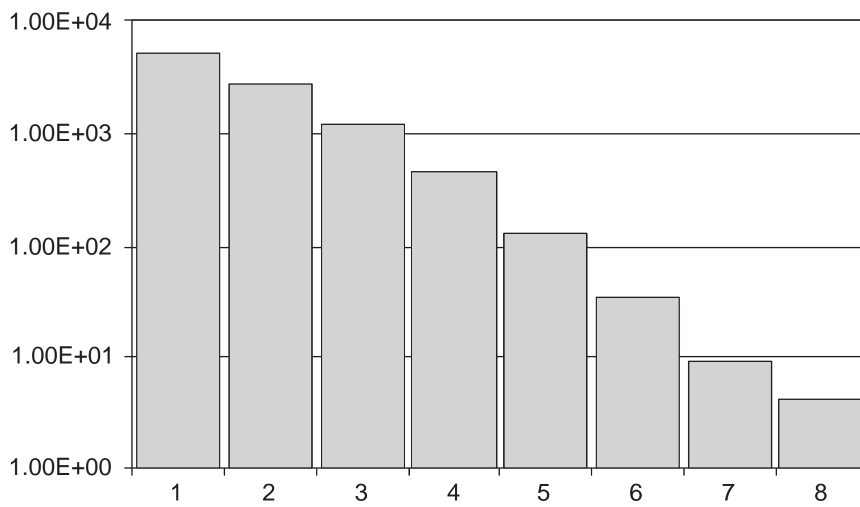


Figure 8 is a chart plotted in semi-log scale.

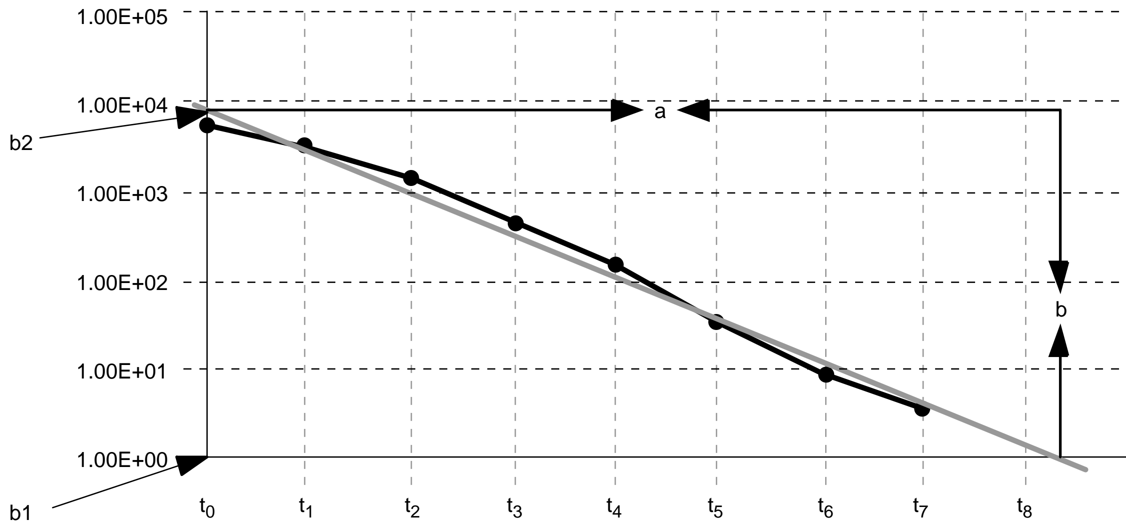
Figure 8. Semi-log Scale Chart



For calculation purposes, the column style chart is converted to a line style in Figure 9.In this plot, each mask is represented by a time unit. The straight line with no data points is the approximation of the actual data for calculation.

Measurement Example

Figure 9. Plot of the Metastability Decay versus Time



DUT: LC4128C-27T100C

f_C = 40 MHz
f_D = 40 MHz (Data rate, not data frequency measured as clock frequency)

W measurement,

tco_max_begin: 12.880, ns
tco_max_end, : 12.910, ns
W = 12.910 ns - 12.880 ns = 0.30 ns = 3E-11 s (10)

Mask size (ps) = 100 ps = 1E-10 s
Total mask span = 8.3
V_{OH} min = 1.6V
V_{OL} max = 0.2V

From the exponential decay function we now can derive the slope of the curve:

$$-1/ \tau\delta = b/a = [\log(b2) - \log(b1)] / - (\text{mask size} * \text{total mask span}) \quad (11)$$

$$= - [\log(7.08E+03) - 0] / (1E-10 * 8.3) = -4638554210$$

$$= 2.156E-10$$

Note: If the slope (-1/τ is calculated in natural logarithm [ln(b2) - ln(b1)], Equation 7 will produce the same result.

Now, the available resolution time in the test set-up is from Equation 1,

$$t_R = (1 / fc - tco_max - tsu_min) \quad (12)$$

$$= (1 / (4.0E+07) - (2.7E-09) - (2.0E-09) = (2.03E-08)$$

where :

tco_max = 2.7 ns = 2.7E-08 s
tsu_min = 2.0 ns = 2.0E-08 s (from data sheet)

From Equation 9,

$$MTBF = 10^{tr/\tau\delta} / (W * Fc * Fd) \quad (13)$$

Substitution of all values results:

MTBF = 1.81E+88 seconds or 5.76E+80 years, which is almost forever

Summary of Metastability Characteristics

- Metastability is dependent on device technology.
- The constants, τ and W are fixed for each device with the same speed grade.
- The exponential nature of the MTBF formula is extremely sensitive to small changes in tr and τ.

Table 2. Metastability Data of Lattice Devices

Part Number	W (ps)	Max. Available t_R (ns) @ Fc	τ (ps)	f_C[2] (MHz)	f_D[2] (MHz)	t_R (ns) for 10 Year MTBF[1]
ispLSI 2128VE-100LT100	40	38.5	220	20	20	6.43
ispLSI 5256VE-125LT100	20	10.5	176	50	50	5.15
ispLSI 5384VA-125LQ208	25	15.0	181	40	40	5.46
LFX1200C-03F900C	70	9.5	45	50	50	1.44
LX256B-35F484	20	11.6	35	50	50	1.06
M4A3-128/64-10VC	25	13.5	53	40	40	1.59
ORT82G5-3BM680C	15	19.2	49	50	50	1.48

1. Assumes that all other parameters are same as the test conditions with maximum available t_R and f_C and f_D, as specified in the table.
2. f_C and f_D are arbitrarily chosen for measurement.

References

[1] Clark Foley, “Characterizing Metastability,” 1996 IEEE
[2] Howard Johnson, “High-Speed Digital Design,” 1993, pp120-131.
[3] Ran Ginosar, “VLSI Lecture 10: Synchronization(I)”, 2003
[4] K.U. Leuven, “Fault-Tolerant Computing” 2000 ESAT/ACCA

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