Reduced Test Time for HCI and Electromigration Tests

Many Reliability "Wear-out" tests monitor a performance parameter that degrades steadily with the log of the time on stress. In most cases, a time to 10% degradation is measured. The time to 10% degradation is considered a benchmark because many devices are tested speeds or voltages that are 10% above the certified capability of the semiconductor devices. For example, a DRAM might be tested and found to be fully functional with a 45ns. access time but sold as a slower 50ns. device. This "guard-banding" allows the critical performance parameters to drift by up to 10% without causing the device to fall outside of its specified performance. The reliability test must then prove that the device will not experience more than a 10% drift in the critical performance parameter over the expected product lifetime (typically 10 or 20 years).

The time to 10% degradation can be measured at accelerated conditions in order to obtain a measure of this degradation in a shorter period of time. However, this requires a good knowledge of the failure mechanism in order to be able to extrapolate the results to find the time to 10% degradation at the use conditions. In most cases, this will require testing at several different stress conditions in order to extract the relationship between the stress condition and rate of degradation. This multiplies the cost of the test and limits the test time reduction to what can be obtained using the lowest stress condition.

The maximum stress conditions are typically limited by parasitic considerations such as joule heating or source-drain punch-through voltage. Additionally, competing failure mechanisms can cause a change in the tested failure mechanism at higher stress conditions (e.g. the change from grain boundary diffusion to bulk diffusion at higher temperatures for electromigration tests). This limits the acceleration that can be applied to the highest stress condition.

An alternative technique is to measure the time to a smaller percent degradation at the true use conditions. Since the rate of degradation is generally linear in the log time domain, a smaller percentage change in the measured degradation can be measured in a much shorter test time. The use of "use condition" stress levels in such a test will allow testing at only one stress condition, and will remove the requirement to understand the stress vs. time relationship. Additionally, there will be no concerns that the higher stress conditions will change the rate of degradation.

However, the use of this technique will require very low instrumentation noise levels and very good time resolution.

Consider the rate of degradation seen in figure 1. The transistor exposed to a "use condition stress" is found to degrade at a rate of 10%/decade. With this slope, the requirement of degradation of less than 10% in 10 years means that the device must show less than 9% degradation in 1 year and less than 8% degradation in 1/10 year, or 36.5 days, Further, it must show less than 7% degradation in 3.65 days and less than 6% degradation in 0.365 days or 8.76 hours. If a test is to be conducted with a test duration of 8.76 hours, then the results will have to be extrapolated over 4 decades in time. For this extrapolation to have any meaning, we must be able to show data accumulated over at least 4 orders of magnitude in time. This will mean that the minimum time resolution must be

3.15 seconds. At 3.15 seconds, we would expect to measure a degradation of only 2%. To measure this value accurately, we would need a measurement noise of less than 0.2%.

All of this sounds very possible. However, these requirements are clearly a function of the rate of degradation. Figure 1 shows several different rates of degradation all resulting in a 10% degradation in ten years. Table 1 shows the minimum time and minimum instrument resolution to measure and extrapolate these results with an 8.76 hours stress.

Table 1: Instrument Resolution				
Rate of Degradation (%/decade)	10%	20%	200%	500%
Minimum Time Resolution (seconds)	3.15	3.15	3.15	3.15
Minimum Instrument Resolution	5.13%	2.79%	0.039%	2.56E-5%

Table 1: Lower Instrument Noise Required for Steeper Rates of Degradation

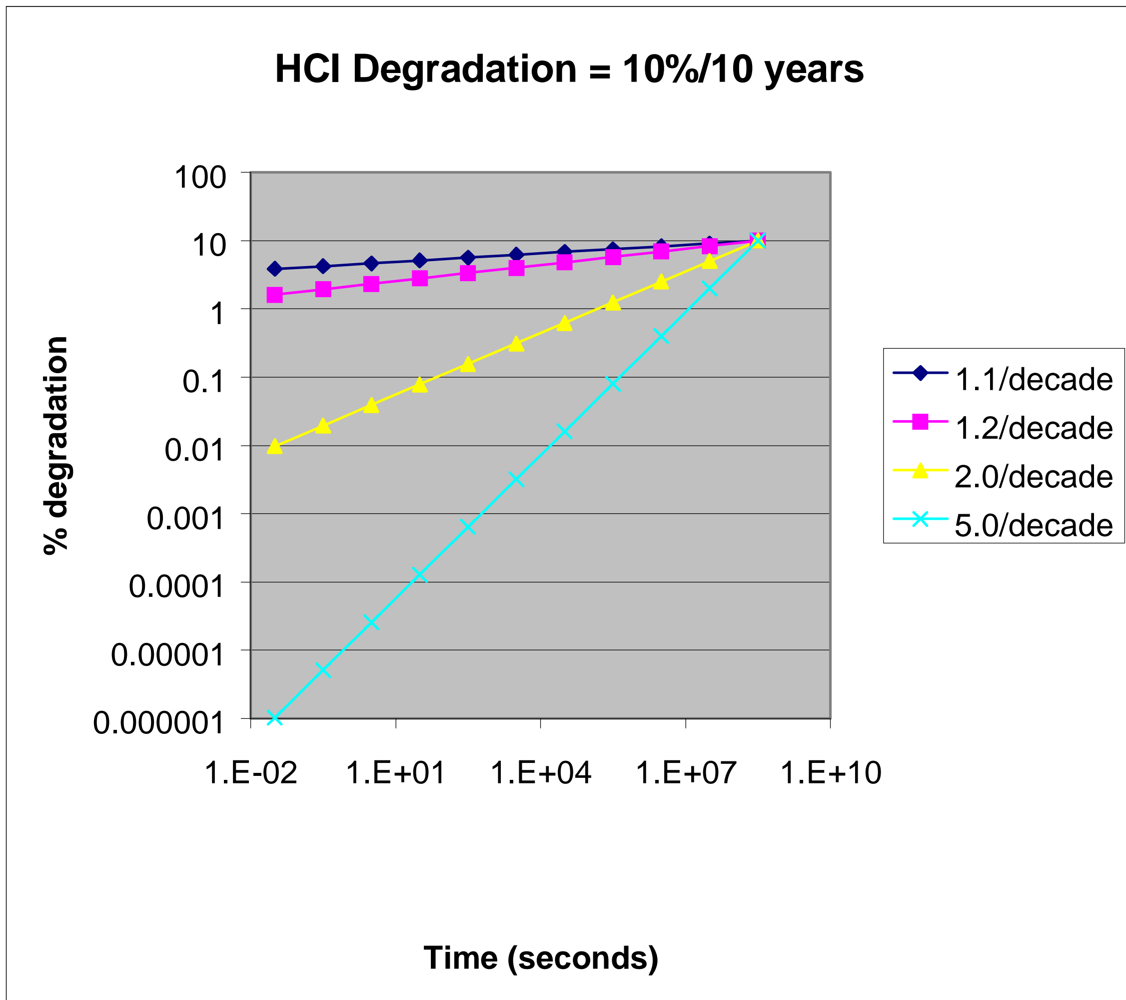


Table 1 clearly shows that the steeper the rate of degradation, the lower the instrumentation noise required to measure the degradation with a fixed test duration. Looked at another way, this data can be used to determine the minimum test time given the instrument noise.

From figure 1 it can be seen that the minimum time point can be extracted from any of the curves by reading across the graph at 10X the instrumentation noise to determine the minimum time were this value will be recorded. For example, in figure 1, an instrument with a noise level of 0.01% will have a 10X noise value of 0.1%. Looking across the graph at 0.1% it is clear that the minimum stress time for the very low slopes (10% and 20%/decade) can be very short. However, for the 200%/decade (doubles each decade) the minimum time would have to be about 20 seconds. For the 500%/decade slope, the minimum stress time would have to be about 30,000 seconds, or 8.3 hours. This is the point where a device that will fail the 10% in 10 year goal will show degradation that is 10X the measurement noise. The total test time to allow a good projection of the degradation at 10 years must be much longer than these values.

For the 200%/decade slope, there are about 7 orders of magnitude between the point where the first accurate measure of the degradation can be measured and the 10 year point (315 million seconds).

Half that difference is 3.5 orders of magnitude or 3162 time the minimum value. This will give a minimum test time of 63240 seconds or 17.5 hours. This will allow the accurate measurement of the degradation over 3.5 orders of magnitude and the extrapolation of the slope over 3.5 orders of magnitude.

For the 500%/decade slope, the first accurate measure of the degradation will occur at 30,000 seconds. This leaves only 4 orders of magnitude of time between this first point and the 10 year point. The extrapolation must then cover only 2 orders of magnitude in order to accomplish the goal of extrapolation over a distance no longer than the measured range. This requires a total measurement time of about 3 million seconds, or 35 days.

Obviously, a lower instrumentation noise margin is very valuable. If the measurement noise could be dropped from 0.01% to 0.003%, the test duration could be reduced from 35 days to about 16 days. Clearly there is a relationship between instrumentation noise, test duration and application lifetime. The minimum test duration will be:

$$t_{min} = 10\hat{}((\log(t_{life}) - \log(t_{noise}))/2 + \log t_{noise}) \qquad 1.0$$

Where: t_{noise} = the time required for the sample to show a shift in the measured parameter that is ten times higher than the noise level for the instrument.
t_{life} = the expected application lifetime for the device
t_{min} = the minimum test duration

Equation 1.0 is useful only after the test has started. t_{noise} can not be known before the test has started. This value can only be measured during the test for each device. The test sequence must be as follows:

1. Measure the instrument noise. This is done by making multiple measurements of the performance parameter prior to the start of the test. The noise will be defined as the square root of the sum of the squares of the differences between the individual measurements and the mean of the measurement, divided by the number of measurements.
2. Begin the stress and monitor the parameter until the measured drift in the monitored parameter is greater than 10 times the measured noise.
3. Once the time to drift above 10 times the noise has been measured, the total test time can be calculated based on equation 1.0 above. This value will be half the distance between the 10 times noise point and the expected application lifetime. This will insure that the drift is not extrapolated over a longer range than the data.
4. Continue monitoring the drift in the sample until the calculated test time has been exceeded. All of the points after this point will have measurement noise less than 10% of the measurement.
5. Extrapolate the time to 10% drift based on a least squares fit to the log of the percent change in the parameter vs. the log of time, measured between the time when the measured drift exceeds 10X the noise and the maximum duration of the test.

A complication of this technique is the fact that many N MOS FETs will show an improvement in many measured performance parameters during short stress times. Interface hole traps may actually increase the channel mobility at low gate fields and give a small decrease in the Vt and an increase in the Idlin or Idsat during the first few seconds of the stress.

To account for this effect, it is advisable to measure the maximum (or minimum) for the measured parameter and calculate the change in the parameter from this inflection point rather than from the original (time zero) measurement.

Example 1:

Idlin is measured for a transistor 10 times with no stress in between. The recorded values found are: 10.020, 10.013, 9.990, 10.015, 10.003, 9.985. 9.997, 10.010, 9.990, 10.010 ma. This gives a measurement noise associated with the measurement of Idlin for this transistor of 0.1% for a mean Idlin of 10mA. A hot carrier stress is started with the gate voltage forced to 2.3 volts and the drain forced to 3.7 volts. The Idlin is measured at approximate log time intervals of 3 seconds, 10 seconds, 30 seconds and 100 seconds. These first read-points show an Idlin of 10.101ma, 10.000ma, 9.9ma, 9.8ma. The application lifetime for the product will be 10 years. What is the minimum duration of this stress.

Answer: The measured data shows a maximum Idlin at 3 seconds with a value of 10.101ma. The noise has been measured to be 0.1%, so 10 times the noise subtracted from the measurement will be 1% of the maximum measurement of 10.101. The value of the measurement at 10 seconds is exactly 1% below the peak value. Thus, t_{noise} is 10 seconds. The minimum test duration is now calculated based on equation 1.0 above.

$$t_{min} = 10\text{^}((\log(t_{life}) - \log(t_{noise}))/2 + \log t_{noise}) \qquad 1.0$$

$$t_{min} = 10\text{^}((\log(10\text{ years}) - \log(10\text{ seconds}))/2 + \log 10\text{ seconds})$$

$$t_{min} = 56{,}156\text{ seconds or }15.6\text{ hours}$$

Continuing the test trend started, measurement points of 300 seconds, 1000 seconds, 3000 seconds, 10,000seconds, 30,000 seconds and 56,156 seconds would be taken. If the measurements were consistent with the 0.2%/decade change seen in the first measruements, then the recorded values of the readings would be 9.7, 9.6, 9.5, 9.4, 9.31 and 9.25ma. The least squares fit to this data would project a Idlin of about 8.4ma after 10 years of stress. This would exceed the 10% in ten year goal and the device would fail the test. Since the test was not conducted at an accelerated stress condition, there will be no discussion about extrapolation models or anomalous failure mechanisms. The device has been stressed at the defined “use condition”.

Since every measurement point used in the extrapolation has been at least 10 times the measurement noise, the time extrapolation should be clear. Since the data is not extrapolated beyond the time range of the data, the risk in the time extrapolation is low as long as the least squares fit is good.

It should be very clear that the use of this technique requires low measurement noise. If the measurement noise is on the order of 1% of the measured value, then there is no time savings associated with this technique. The time to 10 times the noise will be the time to 10% degradation so there will be no need to extrapolate the measured value and no time savings.

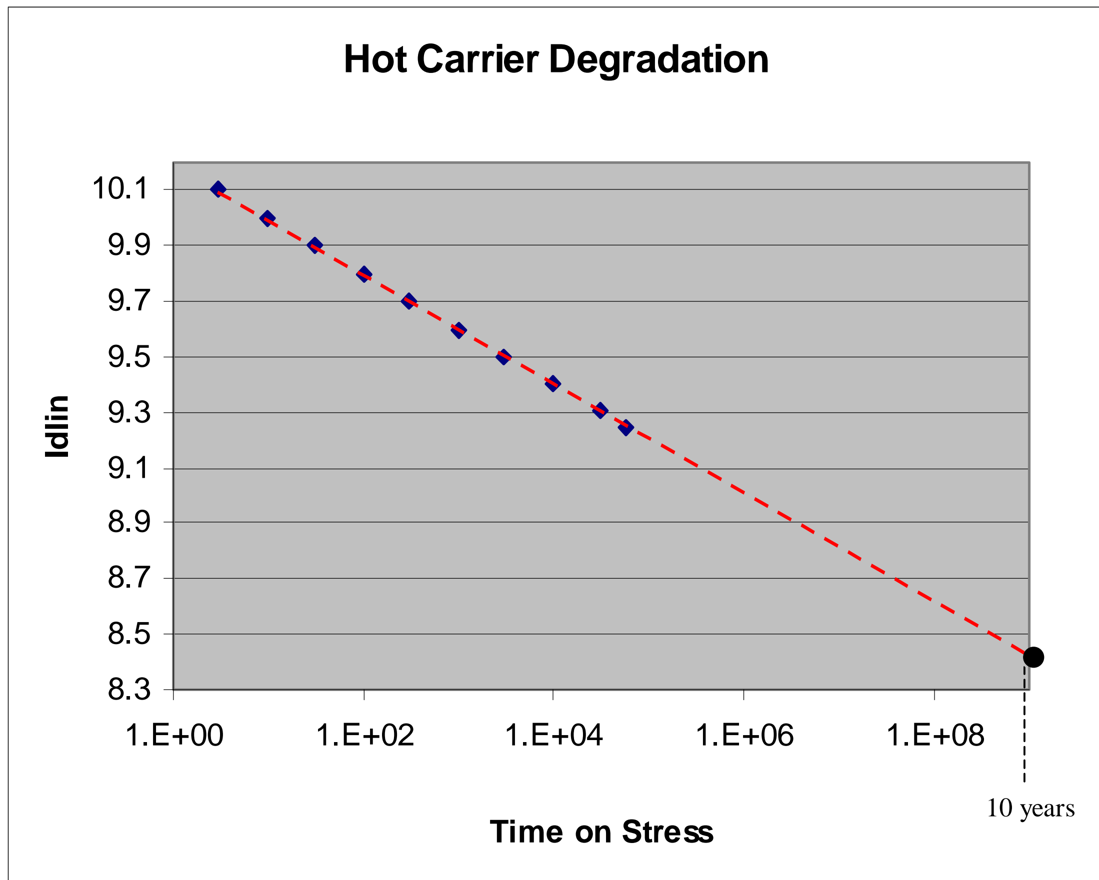
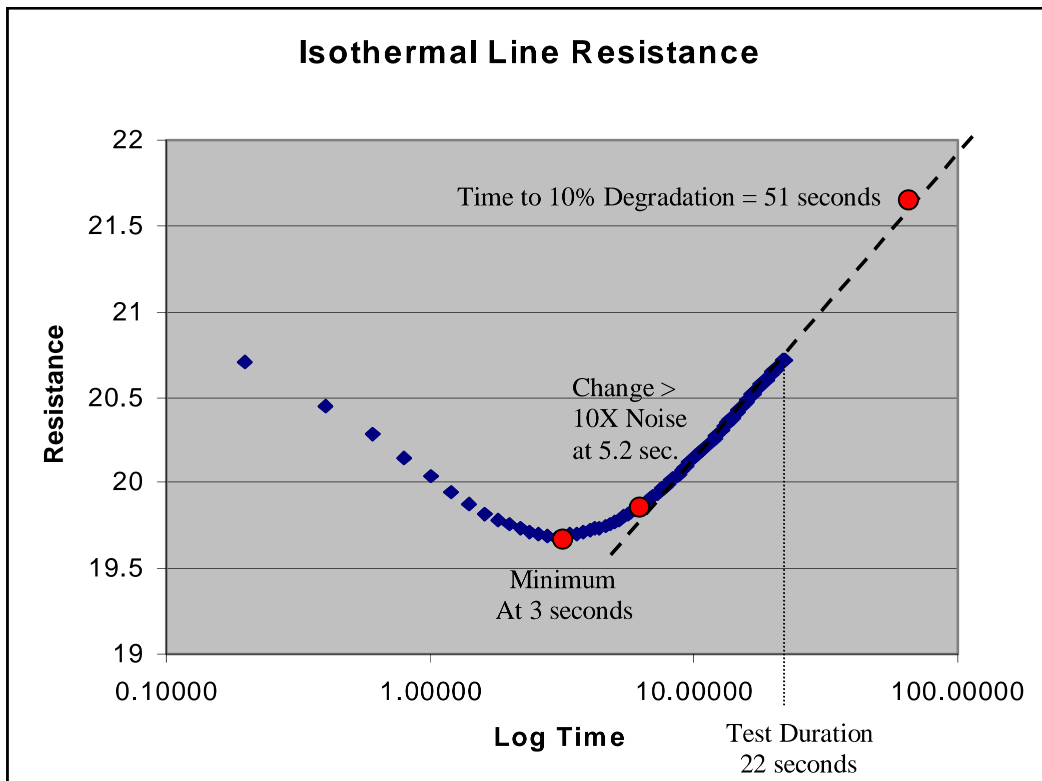


Figure 2: Lifetime Extrapolation

While most of the discussion above has concerned hot carrier lifetime extrapolation at use condition stresses, the same technique can be used to minimize test time for accelerated electromigration tests. Once again, the device is expected to show a degradation that is linear in the log time domain. Figure 3 shows the change in resistance vs. time for a metal line subjected to an Isothermal electromigration test (JEDEC standard JESD61).
Figure 3 again shows the metal line resistance initially dropping as a function of time. This is due to annealing effects in the line at the high stress temperature (grain growth, precipitation absorption…). The resistance hits a minimum at the 3 second readpoint, then begins to increase due to electromigration.



The instrumentation in this example had a measurement noise of 0.05%. Ten times this noise is 0.5%. The data showed that the measured change in resistance above the minimum was greater than 0.5% at the 5.2 second read-point. This read-point occurred 2.2 seconds after the minimum resistance was recorded. All measurements after this point should show the measurement noise comprising less than 10% of the measured degradation. The test was then continued for one order of magnitude in time beyond this minimum measurement point. A order of magnitude of time with the measured signal more than 10 times the measurement noise should allow the accurate extrapolation of the time to 10% degradation at this stress level. For this example, the test was terminated after 22 seconds. If the test had been continued until the time to 10% degradation could be measured, the test would have taken 51 seconds. Thus this technique was able to reduce the total test time by more than a factor of 2.3. This can be very important for a fast process control test.