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WHITE PAPER

Reduced Test Time for HCI and Electromigration Tests

Many reliability "wearout" 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 at speeds or voltages that are 10% greater than 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 then sold as a slower 50ns device. This "guard-banding" allows for a drift of up to 10% in the critical performance parameters without the device falling outside of its specified performance. A reliability test must prove that the device will not experience a critical performance parameter drift of more than 10% over the expected product lifetime (typically ten or 20 years).

Accelerated stress levels can be used to obtain a measure of the time to 10% degradation in a shorter period. However, a good knowledge of the failure mechanism is required in order 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 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.

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An alternative technique is to measure the time to a smaller percent degradation at the true use conditions. Given that 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 eliminate the need 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 short 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 ten years means that the device must show less than 9% degradation in one year. This can be extended to require 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 four decades in time. For this extrapolation to have any meaning, we must be able to show data accumulated over at least four 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%. Measuring this value accurately requires less than 0.2% measurement noise.

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-hour stress.

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

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 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 if the instrument noise is given.

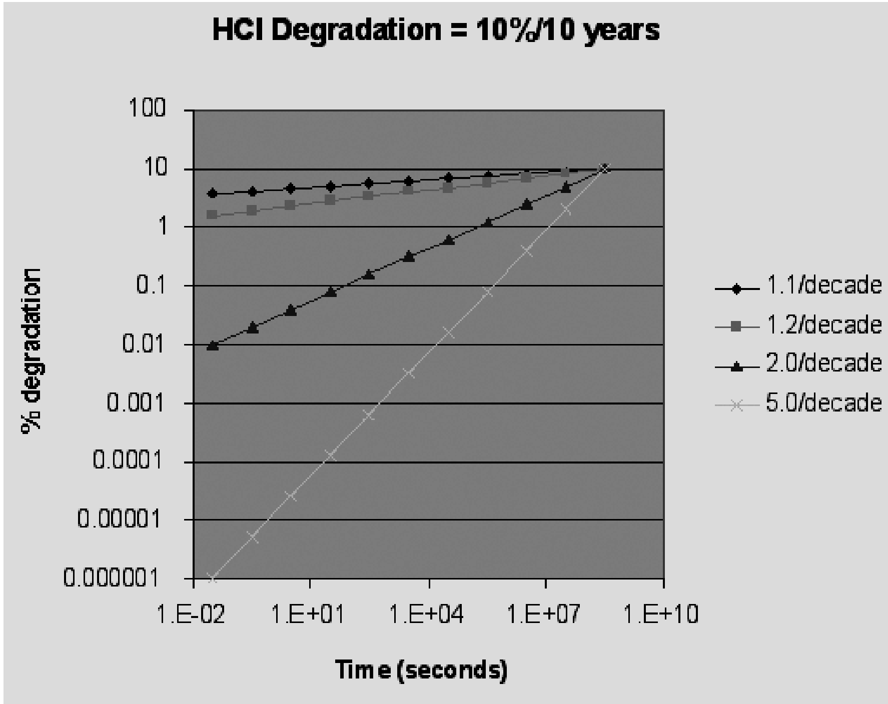

Figure 1. HCI Degradation = 10%/10 years

The minimum time point can be extracted from any of the curves in ***Figure*** 1 by drawing a line on the graph to represent 10× the instrumentation noise. The point where this line intersects the curves represents the minimum time at which the instrumentation noise can be considered a minor effect. For example, in ***Figure 1***, an instrument with a noise level of 0.01% will have a 10× noise value of 0.1%. Drawing a line 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 at which a device that will fail to meet the goal of 10% in ten years will show degradation that is 10× the measurement noise. The total test time to allow a good projection of the degradation at ten years must be much longer than these values.

For the 200%/decade slope, there are about seven orders of magnitude between the point where the first accurate measure of the degradation can be measured and the ten-year point (315 million seconds). Half that difference is 3.5 orders of magnitude or 3162 times 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 four orders of magnitude of time between this first point and the ten-year point. The extrapolation must then cover only two 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 three 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:

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

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

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

1. Measure the instrument noise 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 ten times the measured noise.

3. Once the transistor has shifted by an amount greater than 10× the measurement noise, we will have a measurement of the time required to induce this parametric shift. This “time to 10× noise” will allow us to calculate the total test time based on ***Eq. 1.0***. This value will be half the distance between the “ten times noise point” and the expected application lifetime. This will ensure that the drift is not extrapolated over a longer range than the range of the data.

4. Continue monitoring the drift in the sample until the calculated test time has been exceeded. All of the points that follow 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 10× the noise and the maximum duration of the test.

Many NMOS FETs will show improvement in some measured performance parameters during short stress times. This complicates the use of the "use condition" technique. 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 I_{dlin} or I_{dsat} 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:

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

Answer: The measured data shows a maximum I_{dlin} at three seconds with a value of 10.101mA. The noise has been measured to be 0.1%, so ten times the noise subtracted from the measurement will be 1% of the maximum measurement of 10.101. The value of the measurement at ten seconds is exactly 1% below the peak value. Thus, tnoise is ten seconds. The minimum test duration is now calculated based on ***Eq. 1.0.***

t_{min} = 10^((log (t_{life}) – log(t_{noise}))/2 + log t_{noise}) 1.0

t_{min} = 10^((log (10 years) – log(10 seconds))/2 + log 10 seconds)

t_{min} = 56,156 seconds or 15.6 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 measurements, 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 an I_{dlin} of about 8.4mA after ten years of stress. This would exceed the goal of 10% in ten years 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.”

Every measurement point used in the extrapolation has been at least ten times the measurement noise, so the time extrapolation should be clear (***Figure 2***). Since the data is not extrapolated over a range greater than the valid data range, the risk in the time extrapolation is low as long as the least squares fit is good.

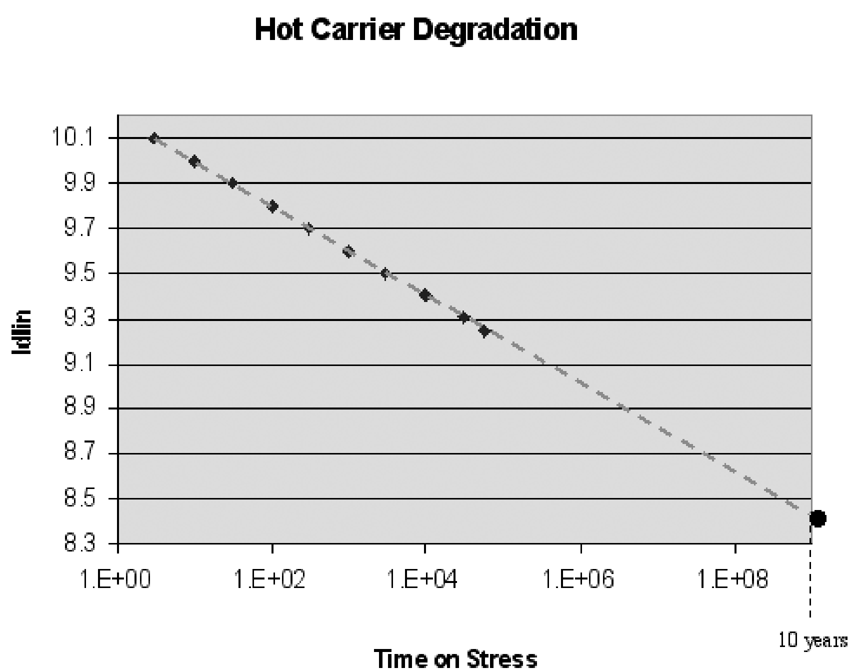

Figure 2. Lifetime extrapolation

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 ten 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.

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).

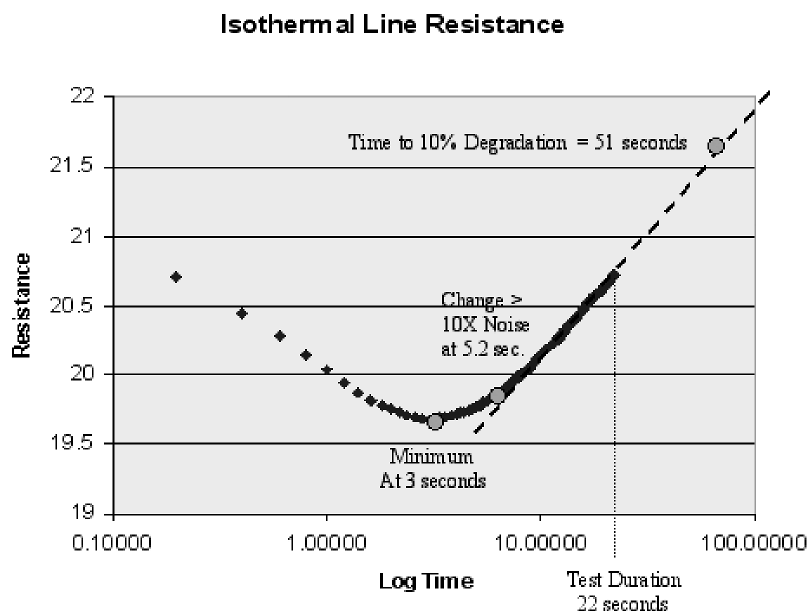

Figure 3. Isothermal line resistance

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, etc.). The resistance hits a minimum at the three-second readpoint, then begins to increase due to electromigration.

The instrumentation in this example (***Figure 3***) 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 readpoint. This readpoint 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. An order of magnitude of time with the measured signal more than ten 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.

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