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TLP Systems with Combined 50 and 500-ohm Impedance Probes and Kelvin Probes

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Abstract - TLP systems are mainly classified by their impedance, such as 50 ohm or 500 ohm current source. A new TLP configuration allows switching between 50 and 500 ohm by computer control to characterize a given part using both impedances. In addition, a four-needle Kelvin technique is introduced to TLP, which overcomes the measurement error from variations in contact resistance where the probe needles contact the wafer surface.

I. Introduction

In classifying Transmission Line Pulse (TLP) systems, the impedance of stress pulses delivered to the device under test (DUT) and the pulse transmission cable topologies are major items of differentiation. Probes used to contact wafer pads play a critical role in performance of wafer level TLP systems because their design can control impedance and determine the mode of TLP systems. Probe configurations may define the TLP operating mode due to their loading impedance, which can make the difference between Time Domain Reflection (TDR), Time Domain Transmission (TDT) and Current Source (CRS) systems. Besides the dynamic loading effects, the probe needles exhibit a contact resistance which can be several ohms and is not consistent. Contact resistance limits measurement accuracy with low resistance DUTs.

New types of probes[†] have been developed that add flexibility and increase accuracy of TLP measurements. One probe set can switch impedance between 50 and 500 ohms pulse delivery impedance to accurately measure snapback response when the high impedance is used, and to also produce high DUT currents for failure point analysis in the low impedance mode.

Four-wire or Kelvin probes have been developed that separate the stress pulse application from the sensing of TLP voltages. This prevents contact resistance from affecting the DUT voltage measurements.

II. Combined 50 and 500-ohm Impedance Probes

The pulse transmission path is quite different in 50-ohm TLP systems compared with 500-ohm, or Current Source, systems. While a few custom systems have the ability to be converted between 50 and 500-ohm operation, this conversion requires cabling and component changes. A newly developed TLP configuration, however, makes it possible to switch between 50 and 500-ohm operation by computer control.

One significant advantage of 500-ohm systems is the ability to measure holding current more accurately on ESD protection structures that demonstrate a snapback when they turn on. On the other hand, 50-ohm systems can deliver ten times the current at the same voltage allowing failure point determination of high current device structures.

The new TLP configuration, with the ability to switch between 50 and 500-ohm operation, has the advantages of both systems. This new technique allows TLP measurements with both impedances to be taken on the same part during a single stress pulse sequence.

[†] U.S. patents pending.

A. The 50-ohm TDR System

The basic 50-ohm system uses current and voltage probes to measure incident and reflected pulses. A traditional TDR mode of TLP uses a delay cable between these sensors and the device under test (DUT) so that the incident and reflected pulses are separated in time and are individually measured and mathematically combined to determine the DUT voltage and current. However, by packaging the sense probes in a measurement pod and placing them close to the wafer probe needles, the overlap of incident and reflected pulses is measured. TDR with overlapped pulses, or TDR-O, results where the oscilloscope directly measures the current and voltage of the device under test. When the incident and reflected pulses are overlapped, the TLP measurements are taken directly from oscilloscope data: $V_{DUT} = V_{SCOPE}$ and $I_{DUT} = I_{SCOPE}$.

Figure 1: Current and Voltage Measurement pod

In a standard 50-ohm TLP system, the pulse is delivered through a 50-ohm needle to the DUT and a ground probe serves as the current return path as can be seen in Figures 2 and 3.

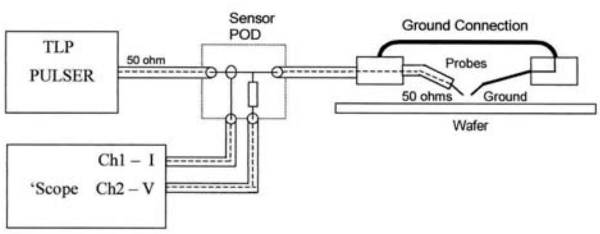

Figure 2: 50-ohm Wafer Level TDR TLP Diagram

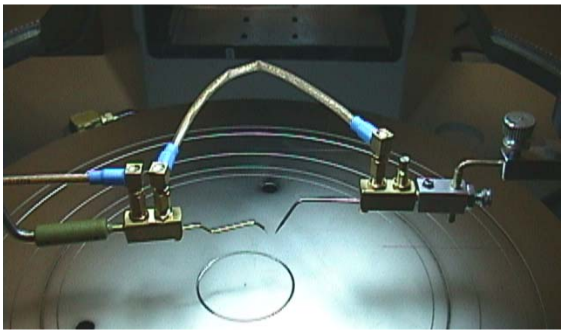

Figure 3: Standard 50-ohm and Ground Probes

B. The 500-ohm System

The new technique replaces the ground probe with a 450-ohm probe as shown in Figure 4. This special 450-ohm probe needle assembly provides a scope signal (basically a 9X scope probe).

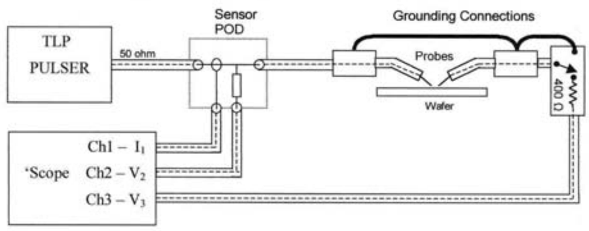

Figure 4: 500-ohm Wafer Level TLP Diagram

Furthermore, the special probe shown in Figure 4 has a relay that can ground the probe signal, and thereby allows it to function in a manner identical to the standard ground probe of Figure 2. This switch between a direct ground and a 450-ohm scope probe produces the impedance change from 50 to 500 ohms. The relay also provides a direct ground for the DUT, which is needed for DC leakage measurements.

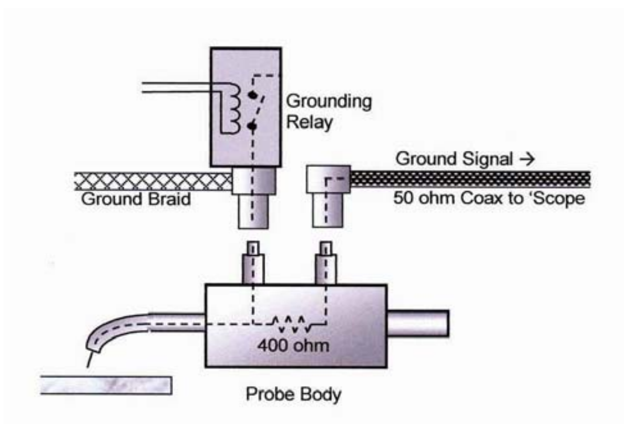

Figure 5: 450-ohm Probe Diagram

The TLP measurement values are calculated from oscilloscope data: $V_{DUT} = V_1 - K \cdot V_3$, where V_1 and V_3 are scope measured values from recorded waveforms on channels 1 and 3, and probe attenuation factor $K \approx 9$; $I_{DUT} = I_2$ or $I_{DUT} = \frac{V_3}{50}$, where I_2 is data from the current probe recorded on scope channel 2, V_3 is the voltage recorded on scope channel 3, and 50 is the scope input impedance of channel 3. As the above equations imply, the DUT current can be measured by two independent methods in the 500-ohm mode. The standard current probe measures the current of the reflected and incident pulses determining DUT current in the normal TDR fashion. The second method utilizes the 450-ohm probe allowing the scope to measure the probe current via the voltage generated across the scope's 50-ohm input. The 50/500-ohm needle assemblies are shown in Figure 6.

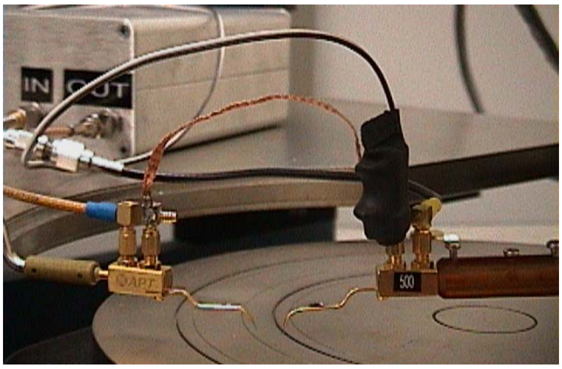

Figure 6: The New 50/500-ohm Probe System

C. Performance of 50/500 System

The system operation is controlled by a computer with a graphical user interface as shown in Figure 7.

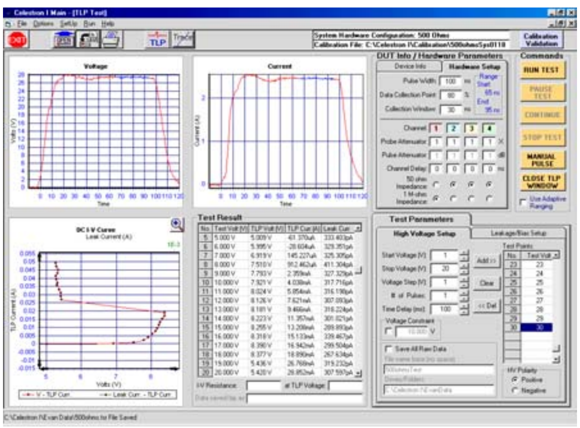

Figure 7: System Display showing Data in 500-ohm Configuration

The 500-ohm I-V Plot shows more detail about the snapback, or turn-on characteristics, than does the 50-ohm I-V Plot as demonstrated in Figures 8 and 9. When snapback occurs in the 50-ohm plot (Figure 8) the lowest holding current (I_{HOLD}) that is measured is 90.4 mA, while the 500-ohm system (Figure 9) shows the device behavior in the triggered state from 26.8 mA.

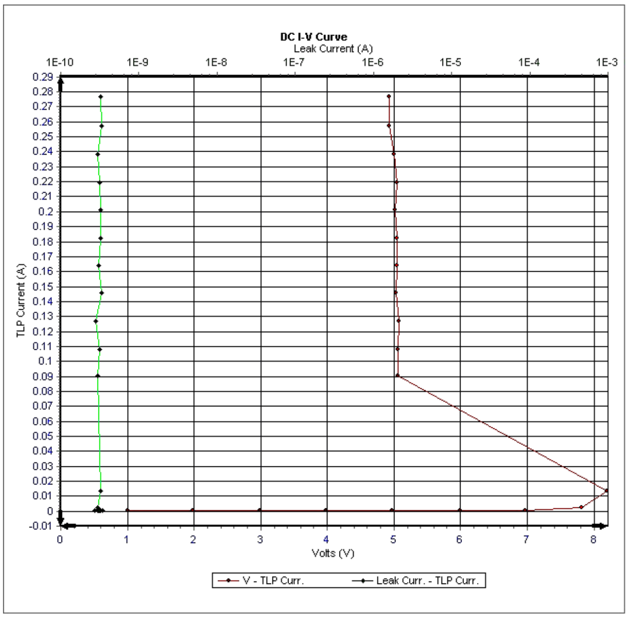

Figure 8: I-V Curve with 50 ohms; leakage is shown on the left

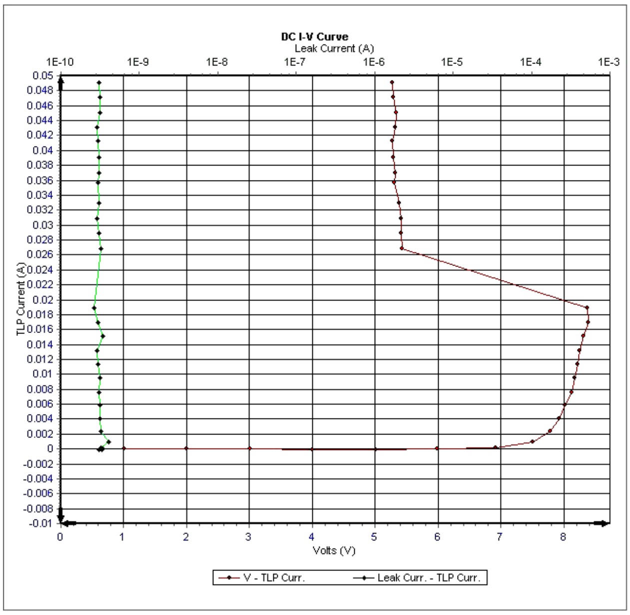

Figure 9: I-V Curve with 500 ohms

The TLP test voltage was stepped in 1 volt increments in both plots. Table 1 shows the same data that is plotted in Figures 8 and 9. Snapback occurs at 10 V of open circuit voltage pulses with 50 ohms, while with 500 ohm the snapback is delayed until a test voltage of 19V which also allows more detailed measurement of the off state behavior (e.g. avalanche current) of the device to be collected.

Table 1: Test Data for the Same Device with Both Impedances

Test Voltage	50 ohm TLP Voltage	50 ohm TLP Current	500 ohm TLP Voltage	500 ohm TLP Current
1	1.00788	.0004159	1.01195	-.000014
2	1.987888	.0004593	1.99406	-.000017
3	2.98734	.0003571	3.00402	-.000035
4	3.988493	.0004269	4.00278	-.000048
5	4.978969	.0003138	5.00917	-.000061
6	5.987748	.0002424	5.99491	-.000029
7	6.972799	.0006173	6.91915	.0000145
8	7.820463	.0024474	7.51029	.0009125
9	8.202899	.0136289	7.79260	.0023592
10	**5.054701**	**.0903844**	7.92060	.0040378
11	5.058862	.1079477	8.02416	.0058538
12	5.073271	.1270819	8.12615	.0076211
13	5.031551	.1457854	8.1810	.009466
14	5.038995	.1638734	8.2232	.011357
15	5.053011	.182605	8.2546	.013209
16	5.0225	.20120	8.3178	.015133
17	5.0402	.21930	8.3897	.016942
18	4.9984	.23838	8.3771	.018890
19	4.9336	.25753	**5.4365**	**.026768**
20	4.9271	.27663	5.4205	.028852
21			5.4123	.030824
22			5.3763	.032906
23			5.3079	.035678
24			5.3258	.036995
25			5.2856	.039041
26			5.2732	.041222
27			5.3147	.043059
28			5.3418	.045036
29			5.2842	.047182
30			5.2743	.049095

D. Calibration of the 50/500-ohm System

Calibration, or systemic error correction, is used to more accurately determine the DUT voltage and currents for creation of a TLP I-V curve. In addition to normal instrument calibrations for voltage and current measurement accuracy, the following corrections are made, to determine system parameters that are in turn used to remove systemic errors.

The measurement pod is connected to the oscilloscope with scope Channel 1 used for the voltage probe, Channel 2 for the current probe, and Channel 3 for the signal from the 450-ohm probe.

1. Error Correction Steps in the 50 ohm mode

1. Short the DUT probes together simulating a DUT of zero resistance and record the measured TLP voltage, V_m, and the TLP current, I_m, and calculate the system series resistance $R_S = \frac{V_m}{I_m}$.
2. Open all connections of the DUT probes simulating a DUT of infinite resistance and record the measured TLP voltage, V_m, and the TLP current, I_m, and calculate the system shunt resistance $R_{SH} = \frac{V_m}{I_m}$.
3. In subsequent measurements calculate DUT voltage and current, V_{DUT} and I_{DUT}, from the measured voltage and current, V_m and I_m, using $V_{DUT} = V_m - I_m \cdot R_S$ and $I_{DUT} = I_m - \frac{V_m}{R_{SH}}$.

2. Error Correction Steps in 500 ohm mode

1. First perform the 50 ohm correction procedure to obtain R_S and R_{SH}.
2. In the 500-ohm mode, short the DUT probe tips together simulating a DUT of zero resistance and record the measured TLP voltage, V_m, the TLP current, I_m, and the voltage from the 450-ohm probe, V_3. Then calculate the 450-ohm probe attenuation factor, $K = \frac{V_m - I_m \cdot R_S}{V_3}$.
3. In subsequent measurements calculate DUT voltage and current, V_{DUT} and I_{DUT}, from the measured voltages and current, V_m, I_m, and V_3 using $V_{DUT} = V_m - I_m \cdot R_S - V_3 \cdot K$, and $I_{DUT} = I_m - \frac{V_m}{R_{SH}}$.

III. Kelvin (4-Point) Probes

TLP testing accuracy on wafers is limited by probe needle resistances. Test probe needles have tips of 10 to 50 microns radius; and the resulting small contact area produces what is commonly referred to as contact resistance. This contact resistance varies from a fraction of an ohm to several ohms depending on the materials of the needles, the semiconductor wafer contact pad material, the thickness of native oxides that often coat the surfaces of those materials, the overdrive distance used, temperature which can change with the power dissipated from stress pulses, and other conditions. Figure 10 shows individual needle resistances for two 25-needle probe card assemblies as delivered from their manufacturer. This sample of 50 probe needles shows a range of resistances from 1 to almost 4 ohms. With today's low resistance protection structures, these needle resistances can be larger than the on-resistance of the DUT. This causes significant DUT voltage measurement errors.

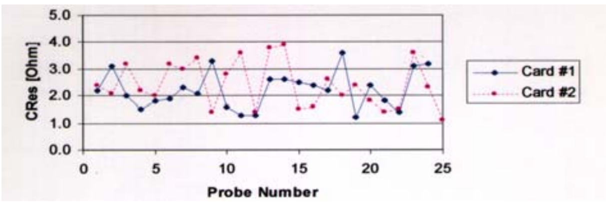

Figure 10: Contact Resistance at 3 mil overtravel

Correction techniques have been published [1], like those described above, that measure system series resistance which includes this contact resistance. With this information, the needle resistances, along with other series resistances, can be taken into account when calculating the DUT voltage and current for each TLP pulse. However, such correction techniques assume that contact resistance is constant and unchanging between the calibration step and subsequent system use. Unfortunately, actual contact resistance varies with each probe needle touch down due to needle and wafer surface conditions such as oxide thickness, hardness of the wafer surface, surface roughness, needle shape (which changes with wear), pressure applied to the needle, composition of the metal IC pad, wafer temperature, and other conditions. Because these contact resistances are not constant, simple calibration methods are unreliable approximations.

The new technique uses the Kelvin-Thompson, or 4-wire, resistance measurement that has long been used for accurate DC measurements. Applying Kelvin probes to the dynamic TLP method however, faces the problems of sense needle loading and reflections from measurement path impedance changes.

A. Dual-needle Kelvin Probes

Adding sense needles contacting the same pads as the TLP force needles allows direct measurement of DUT voltage as shown in Figure 11. If we use 50-ohm probes connecting to 50-ohm scope inputs, a 50 ohm load is added in parallel with the DUT, significantly modifying the measurement system. The TLP system is changed from a 50-ohm TDR system to a 25-ohm TDT system.

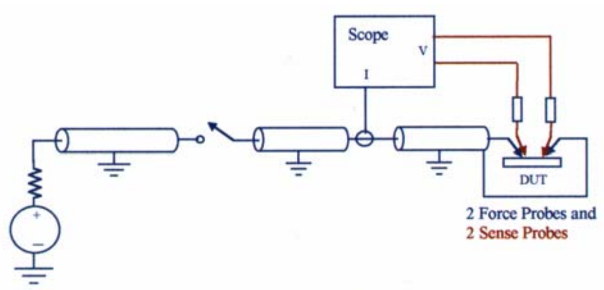

Figure 11: A 4-Point or Kelvin TLP System

To have control over the impedance, we add series resistances in the sense lines close to the DUT making the probes voltage dividers with respect to the 50-ohm scope inputs. The resistors are placed close to the DUT so the pulse reflections they cause are quickly dissipated. The value of these resistors will determine two parameters: impedance driving the DUT, and voltage division ratio to the scope. As the series resistance in the sense lines is increased, the impedance driving the DUT changes from 25 to 50 ohms (in the limiting cases of 0 and infinite series resistances) and the voltage divider ratio changes from 1 to infinity. Choosing the value of 2500 Ω, we make a good engineering compromise: the impedance driving the DUT is 49 ohms, and the sense probes are 50X dividers. This limits the loading (almost all the pulse current is going to the DUT, not to the measurement probe) while allowing low voltage measurements (a DUT voltage of one volt will produce a 20mV signal which is well within the scope's measurement range). With a Kelvin type measurement we do not want the current to the scope to be significant fraction of the pulse current, for if we had large currents through the sense probes we could have a significant I·R drop in the voltage readings. This would partly defeat the purpose of Kelvin probes. Using our 50:1 divider, if the needle resistance changes by 2.5 ohms, the measurement effect is only 0.1%. Since scope measurements will not be effected by typical 2 ohms of contact resistance, any change in contact resistance can now be completely ignored.

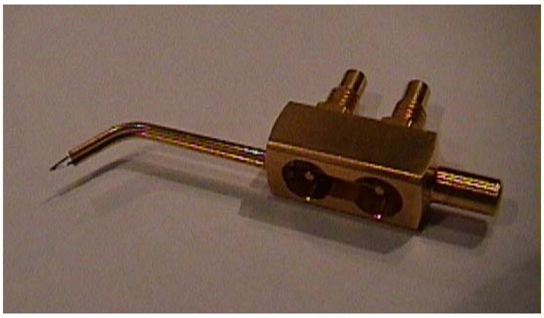

Figure 12: Kelvin Probe body with dual 50 ohm needles are used for both pulse delivery and ground returns

Figure 13: Needles have a 25 micron spacing to allow them to be placed on a single IC pad

B. Multi-needle Kelvin Probe Cards

This technique can be extended from a dual needle pair to multiple needle systems using probe cards made for the DUT pad configuration as can be seen in Figures 14 and 15. Two needles contact each pad of a wafer level DUT. There is a Force Needle and a Sense Needle on each pad. One force needle, the Pulse Force Needle, applies the TLP pulse with one or more other force needles becoming the Ground Force Needle(s). The respectively paired sense needles measure the DUT voltage. The sense needle on the same pad with the pulse force needle becomes the Pulse Sense Needle. The sense needle on the grounded pad is used as the Ground Sense Needle. If there is more than one grounded pad, only one pad is selected to measure the ground voltage.

Key to proper design of structure configuration when doing a Kelvin measurement is the on-wafer pad-to-device wiring, which must be robust and have < 0.1 Ω series resistance to prevent introducing significant error in the device on-resistance due to parasitic wiring.

A 2 by 25 needle probe card was used for measuring DUTs with pads arranged in a column of 25 pads as can be seen in Figures 14 and 15. The needles are tungsten/rhenium for long needle life.

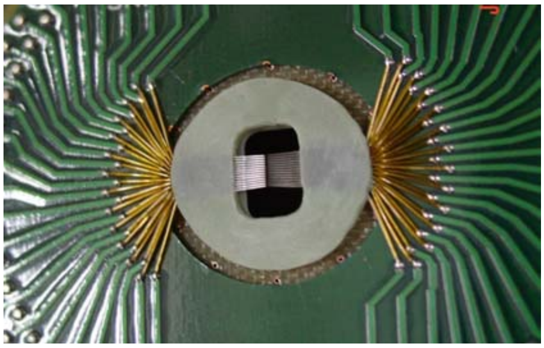

Figure 14: Two rows of 25 needles on probe card

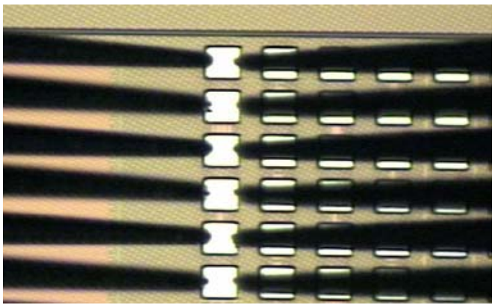

Figure 15: User interface view on a flat panel display shows microscope image of the dual rows of needle tips being placed on wafer pads

To allow any pad to be pulsed, and any other pad to be grounded, there is identical wiring to every force-sense needle pair. The signal paths to the DUT are determined by relay closures as shown in Figure 16.

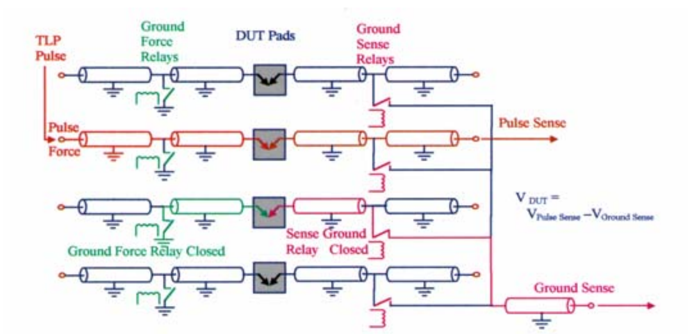

Figure 16: Pulse path through two-row needle assembly

C. Multi-probe Operation

Using a 4-trace oscilloscope, we measure incident and reflected pulse voltages and currents and the voltages directly across the DUT in a differential measurement. Figure 17 shows the measurement waveforms.

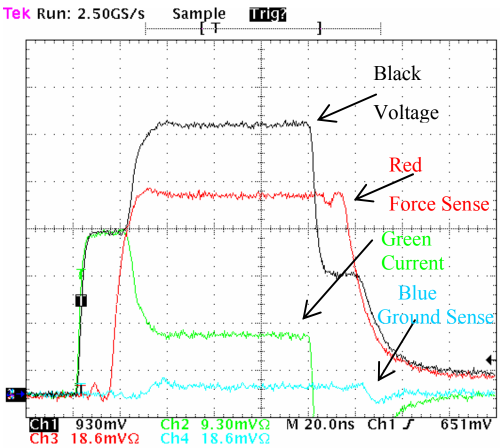

Figure 17: The 4 channel scope waveforms

Channel 1, the **black** trace is TDR-O overlapped TLP voltage incident and reflected pulses, and Channel 2, **green**, is standard current probe measurements of overlapped incident and reflected TLP pulses. The sensed voltage at the pulsed side of the DUT is the **red** Channel 3 trace, while the DUT ground voltage is **blue** Channel 4. The black voltage trace of TDR-O includes the voltage dropped by the DUT and both contact resistances. This is 2-point measurement raw data. The red trace is the pulse sense signal scaled to correct for the probe division ratio; the difference between the black trace and the red trace is due to the pulse force needle contact resistance. The blue trace is the measured voltage at the ground pad, and it is above ground potential due to the force ground needle contact resistance. The Kelvin DUT voltage is calculated by subtracting the ground sense voltage from the pulse sense voltage. The clean waveforms, even with an incident pulse of only 5 volts, show good 4-point signal-to-noise measurements can be made.

D. Multi-probe Performance

Taking TLP measurements on a diode that can withstand currents well above one ampere, we see the benefits of the 4-point Kelvin technique. The diode tested is an n-type diffusion inside the pwell region forming what is referred to as a N+/Substrate (N+ to Substrate) diode which is diagrammed in Figure 18. This specific diode has a failure current near 3A, not shown here but verified with measurements on the same wafer used in this study. We can consider this structure a diode with a series parasitic resistance as shown in Figure 18.

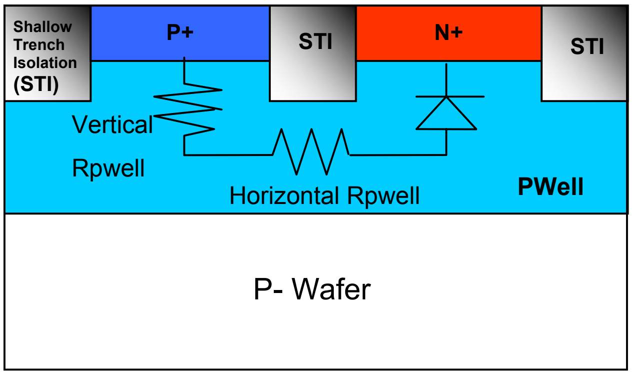

Figure 18: Cross section of the N+/Substrate diode measured

Figure 19 shows the I-V curves of these diodes by testing 5 different chips/die with three methods. The first of the three tests (**black** lines) were done with normal TDR in a 2-point fashion and the raw data was recorded with no correction applied. Then the same set of chips/pads/devices were retested/reprobed after calibrating which measures the system and needle parasitic resistances. Using corrections to the raw data based on this calibration, we recorded the data graphed with **red** lines. Finally the test used the 4-point measurement with its calibration corrections on same 5 chips/pads/devices. This data is plotted with **blue** lines. The 4-point data shows much more consistency and indicates that the actual device-to-device variations observed in two-point measurements were largely instrumentation noise.

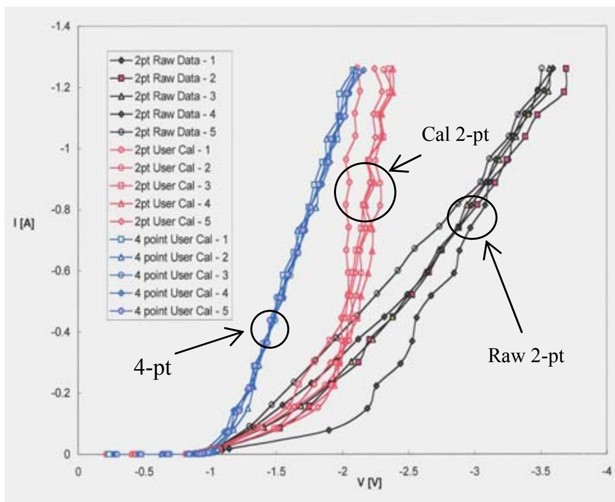

Figure 19: TLP I-V curves on 5 different N+SX Diodes with three tests each, first with standard 2-point, then with Kelvin 4-point wafer probes

The vertical spacing of the data points show very consistent current steps on all traces. Variations among the curves are in the voltage measurements, largely due to contact resistance changes. The improved voltage measurements of the 4-point method demonstrate very reproducible data.

The calibration used in the example above was done with 2-ampere pulses. Even though the data points are at currents below that level, its is clear from a comparison with the 4-point measurements that the 2-point corrections do not remove all probe resistance voltage drops. The error is larger at lower currents. When the calibration was done at 0.2 amperes, the fit was good at low currents but over corrected at higher currents, resulting in the output of a negative resistance slope with increased currents. This indicates that a simple 2-point calibration is inadequate, not due to contact resistance noise, but because the correction needed is non-linear with respect to current. For better 2-point corrections we could calibrate at multiple points and generate a curve representing needle resistances as a function of current, but the complexity of this approach would be a deterrent to user acceptance. Needle wear could also require frequent recalibrations.

The next experiment, shown in Figure 20, repetitively tested a single device. To check reproducibility we measured a diode 15 times. Raw 2-point data was recoded 5 times, corrected 2-point data was taken 5 times, and then 4-point data was measured 5 times. The 4-point measurements occurred after the diode pads had been scrubbed with needles ten times and show no effects from the previous needle damage. The 2-point raw data shows a small increase in resistance between the first and subsequent probings. Again, the 4-point data shows insensitivity to reprobing and good repeatability.

The pads probed here were copper pads from a 0.13um CMOS technology [2,3]. The probe needles chosen were tungsten/rhenium as described previously. The tungsten/rhenium needles do not provide the lowest initial contact/series resistance, however with use they maintain their contact/series resistance better than other materials such as beryllium/copper.

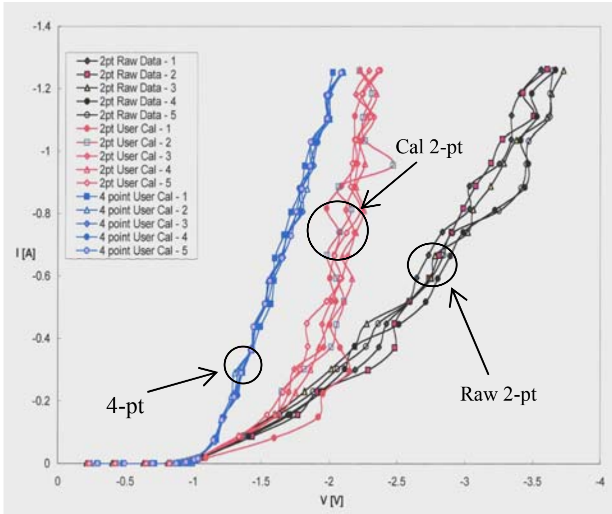

Figure 20: TLP I-V plots of a N+SX Diode retesting the same device 15 times, with standard 2-point and with 4-point probes

E. 4-Point (Kelvin) Probe Calibration

The calibrations used to correct the above data are extensions of the simple open and short measurements used in two needle systems. Pulsing each pin i, one at a time, we find the series resistance R_{Si} and shunt resistance R_{SHi} associated with each pin. The effects of these parasitic resistances can then be removed from subsequent measurements similar to a two-needle system. With 2-point calibration, the needle resistances R_{pfi} and R_{pfj}, shown in Figure 21, are measured and become part of the total series resistance R_{si}. The major error of 2-point calibration is that R_{pfi} and R_{pfj} are not linear, but vary with current as shown in the previous data. R_{ai} and R_{aj} are resistors inserted to reduce loading and to make R_{psi} and R_{psj} negligible when added to R_{ai} and R_{aj}.

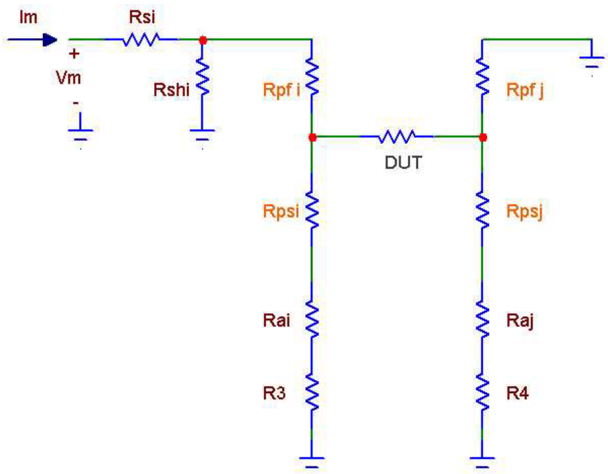

Figure 21: Idealized resistances in the Kelvin measurement

For 4-point Kelvin measurements, we also need to know the signal attenuation from the force pulses to the sensing scope channels. Correction coefficients R_3, K_3 and K_4 for each needle are the attenuation factors for the sense probes. There is no need to deal with needle contact resistances, Rpfi, Rpfj, Rpsi and Rpsj in Figure 21, in 4-point calibration.

Figure 21 shows the measured voltage V_m (recorded by scope Channel 1) and current I_m (from Channel 2). R3 and R4 represent the scope 50-ohm inputs of channels 3 and 4 respectively, and V_3 and V_4 are the voltages recorded by those scope channels, which are voltages dropped across those input resistances.

1. Calibrations Steps for 4-point (Kelvin) TLP

1. With all needles up (open circuit), all force ground relays closed, pulse each pin i, measure Vm_{1i} and Im_{1i} and calculate $R_{Si} = \dfrac{Vm_{1i}}{\mathrm{Im}_{1i}}$, where Vm_{1i} is scope channel 1 and Im_{1i} is scope channel 2 (Note that channel 2, a voltage, is converted to current by dividing by 5, the conversion factor of the Tektronix CT-1 current probe). R_{Si} is the series resistance up to the probe needles.
2. With all needles up (open circuit), all relays open, pulse each pin i, measure Vm_{2i} and Im_{2i}, where Vm_{2i} is scope channel 1 and Im_{2i} is scope channel 2, and calculate $R_{SHi} = \dfrac{Vm_{2i}}{\mathrm{Im}_{2i}} - R_{Si}$. R_{SHi} is the shunt resistance at the probe needles.
3. With needles down on open circuit pad set to connect force and sense pin pairs, all relays open, pulse each pin i, measure Vm_{3i}, Im_{3i} and V_{3i}, where Vm_{3i} is scope channel 1 and Im_{3i} is scope channel 2 and V_{3i} is scope channel 3, and calculate $R_{3i} = \dfrac{V_{3i}}{\mathrm{Im}_{3i} - \dfrac{Vm_{3i}}{R_{SHi}}}$, the effective input resistance of the scope channel 3, and $K_{3i} = \dfrac{Vm_{3i} - R_{Si}\cdot \mathrm{Im}_{3i}}{V_{3i}}$, the measured attenuation from Vm to channel 3.
4. With the needles down on open circuit pad set connecting force/sense pairs, all relays open except close the sense ground relay of the pin being pulsed, pulse each pin i, measure Vm_{4i} (scope channel 1), Im_{4i} (scope channel 2) and V_{4i} (scope channel 4), and calculate the attenuation from Vm to channel 4, $K_{4i} = 1 + \left(Vm_{4i} - \mathrm{Im}_{4i}\cdot R_{Si} - V_{4i}\right)\cdot \left[\dfrac{1}{V_{4i}} - \dfrac{1}{R_{3i}\cdot\left(\mathrm{Im}_{4i} - Vm_{4i}/R_{SHi}\right)}\right]$.
5. For every TLP 4-point measurement, when pulsing pin i and sensing ground from grounded pin j, the DUT voltage and current can be found using the calibration constants for i and j pins:

- $V_{DUT} = K_{3i}\cdot V_3 - K_{4j}\cdot V_4$
- $I_{DUT} = I_m - V_m/R_{SHi} - V_3/R_{3i}$,

where V_m is scope channel 1, I_m is scope channel 2, V_3 is scope channel 3, and V_4 is scope channel 4 voltage.

Figures 22 and 23 show the multi-pin TLP tester.

Figure 22: The TLP 4-point wafer level system

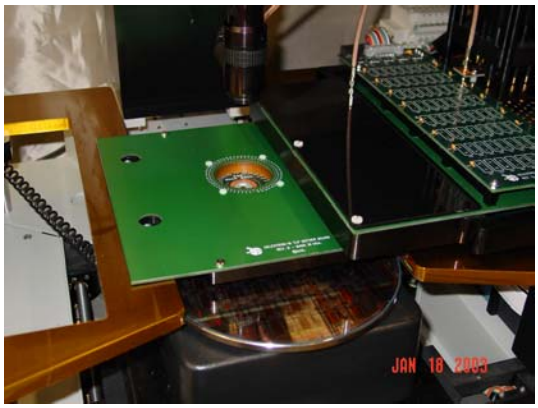

Figure 23: Prober shown with a wafer being measured

IV. Conclusions

New TLP probes with variable impedances and Kelvin measurement capabilities have been shown to have significant improvements for wafer level TLP measurements.

A. Variable Impedance Probes

The new impedance switching probes allow the user to make TLP measurements with 50 and 500-ohm impedances on the same part. This impedance-switching technology produces high quality TLP pulses in both modes. Device failure studies using the high currents of a 50-ohm system and the low current 500-ohm operation for holding current studies are combined in one system. Any impedance of 100 ohms or greater can be produced with a resistor change. For maximum flexibility, a TLP tester using this technique has been built for wafer or packaged device testing where the driving impedance seen at the DUT can be switched by simply selecting the mode from the computer screen.

B. Kelvin Probes

A four-point TLP systems using twin needles and probe cards were designed, built and tested. The voltage measurements made with the sense probes were more consistent due to the removal of I·R drops from contact resistance. The result is more accurate TLP voltage measurements with low resistance DUTs. With the IC pads that the needles contact scaling in area and pitch as the technologies scale, the probe tip area and pitch will continue to get smaller making the probe resistance worse in the future, driving the need for a TLP system with Kelvin measurement capability.

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