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A Procedure to Determine and Correct for Transmission Line Resistances for Direct Current On-Wafer Measurements

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14. ABSTRACT

In this technical note, a procedure is presented that can be used to determine the intrinsic line resistances between a two-port power supply and a device under test (DUT). In order to make an accurate on wafer direct current (DC) measurement, it is necessary to determine the voltages at the terminals of the DUT. As the amount of current that semiconductor devices are capable of handling increases, the voltage drop due to line losses will also increase. A handful of measurements can be used to determine the line resistance, and by using a simple algorithm, the voltage across the DUT can be calculated.

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Introduction

Resistances of tenths of ohms to several ohms in transmission lines have been measured in laboratory systems from the power supply to the device under test (DUT). High current semiconductor devices may draw currents of several amps. In cases such as these, the voltage drop in the transmission lines may rise up to several volts. In order to properly characterize the DUT, the losses in the transmission line and the voltage drop across the line must be measured and accounted for. A procedure for measuring the transmission line resistances is described. Once these values are known, it is necessary to apply a transform to the raw measured data in order to determine the actual voltages on the device of interest. A simple MATLAB code for determining the DUT current and voltage behavior is presented when the raw IV data and the transmission line resistances are known.

Measurements

A three-port device, such as a bipolar junction transistor (BJT), a metal oxide semiconductor field effect transistor (MOSFET), or a high electron mobility transistor (HEMT), when measured on-wafer, may be measured using two separate power lines with ground-signal-ground (GSG) on-wafer probes. Each power supply has two resistances associated with transmission line losses. These are the resistance before the DUT, which will be called the power resistance (R_P), and the resistance after the DUT, which will be called the common resistance (R_C). Each port is identified by number. In our system, Port 1 is normally used to bias the gate on the DUT, and Port 2 is normally used to bias the drain on the DUT.

The direct circuit (DC) power supply used in this experiment was an HP 4142. A block diagram of the DC measurement system is shown in figure 1(a). A circuit diagram of the same system is show in figure 1(b). The HP 4142 has both a force and a sense power cable. The purpose of the sense cable is to directly measure what we are attempting to determine mathematically. For the system used in our experiment, this procedure was not accurate enough. This may be due to the relatively large resistances in the bias T on each side of the DUT. Because the sense cable has its own transmission resistance, it adds an additional degree of complexity to the system that greatly complicates the measurement. In order to use the procedure described, the sense cable should not be used in power supplies that have this feature.

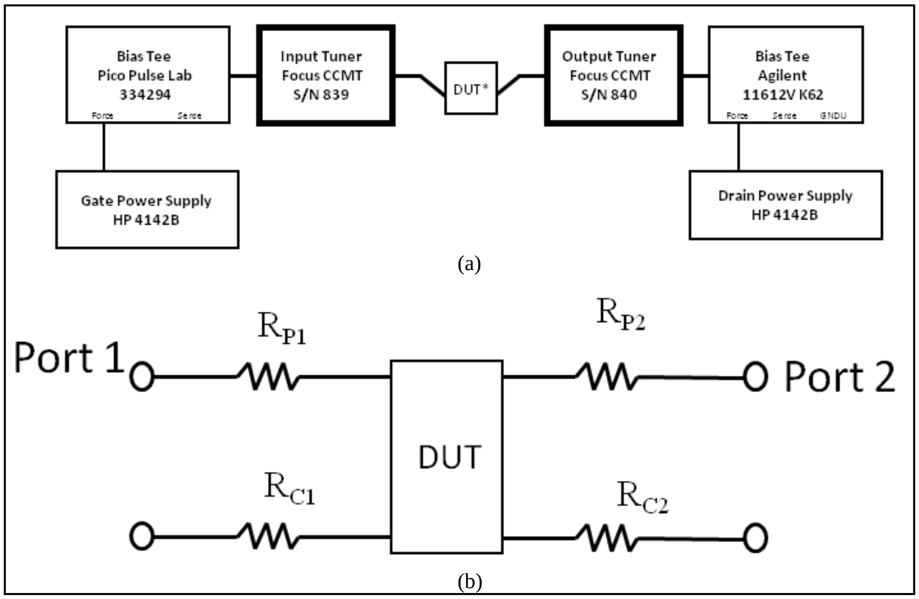

Figure 1. (a) Block diagram of DC measurement system. (b) Circuit diagram of DC measurement system.

As is shown in figure 1(b), the four unknown resistances that need to be determined are R_{P1}, R_{C1}, R_{P2}, and R_{C2}. This will require four separate measurements and four corresponding equations. For each measurement configuration, a separate resistance was recorded. The measurements were made using on-wafer probes. A picture of an on-wafer probe measurement is shown in figure 2.

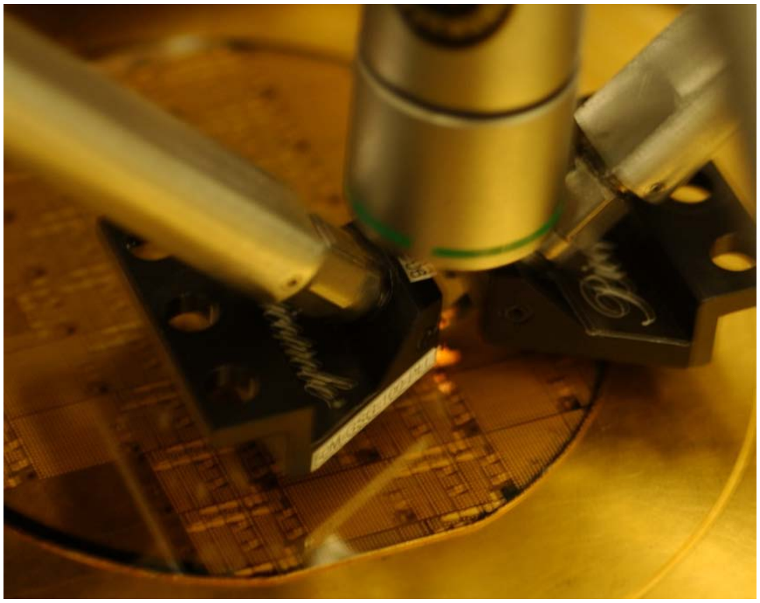

Figure 2. Photograph of on-wafer measurement using ground signal ground probes.

The first measurement is made by shorting the probe on port 1. Figure 3(a) shows a picture of how to land GSG probes onto a metallic standard. The black signifies the probes and the yellow signifies the metallic standard. Figure 3(b) shows the circuit diagram of the measurement. The resistance for this measurement is R1 and is measured by sweeping the voltage across a range of values while recording the current.

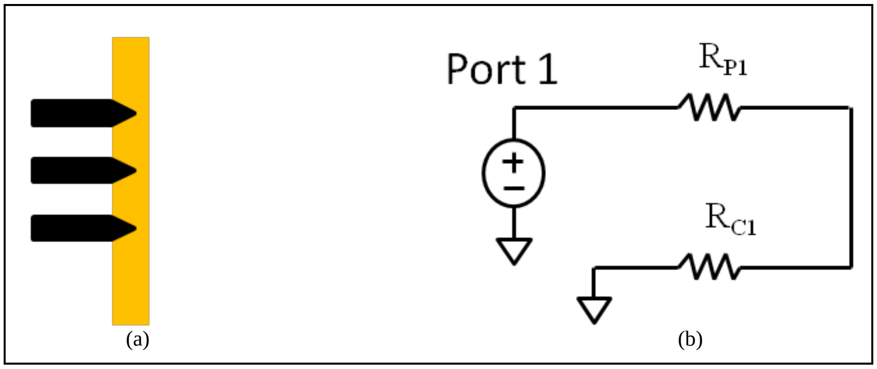

Figure 3. Determination of R1 (a) picture of proper probe placement for short across probe for port 1 and (b) circuit diagram for measurement of R1.

The second measurement is made by shorting the probe on port 2. Figure 4(a) shows a picture of how to land a GSG probes onto a metallic standard. Figure 4(b) shows the circuit diagram of the measurement. The resistance for this measurement is R2 and is measured by sweeping the voltage across a range of values while recording the current.

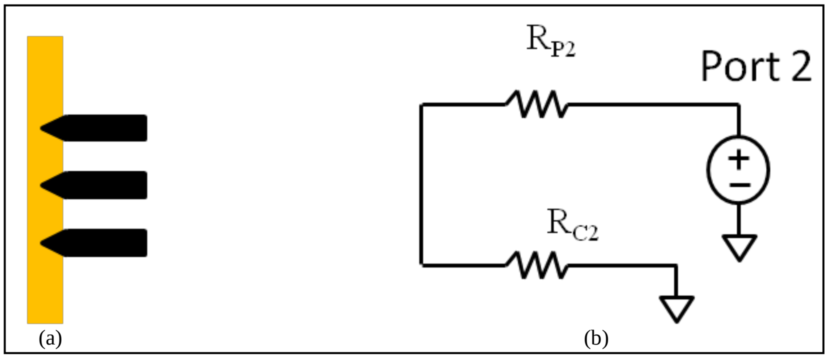

Figure 4. Determination of R2 (a) picture of proper probe placement for short across probe for port 2 and (b) circuit diagram for measurement of R2.

The third measurement is made by landing the probes on a through standard, like the kind typically used in a thru-reflect-line (TRL) s-parameter calibration. Figure 5(a) shows a picture of how to land a GSG probes onto a metallic standard. Figure 5(b) shows the circuit diagram of the measurement. The resistance is measured by setting one of the ports to ground and sweeping the voltage across a range of values while recording the current. This resistance is R3.

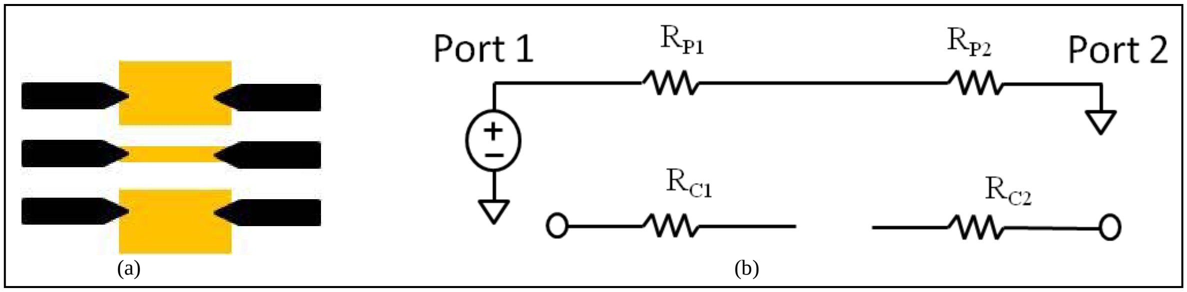

Figure 5. Determination of R3 (a) picture of proper probe placement for thru measurement from port 1 to port 2 and (b) circuit diagram for measurement of R3.

The final measurement is made by landing both probes on a solid metallic standard. Figure 6(a) shows a picture of how to land a GSG probes onto a metallic standard. Figure 6(b) shows the circuit diagram of the measurement. The resistance for this measurement is R4, and is measured be setting the voltage on port 2 to 0 V and sweeping the voltage on port 1 across a range of values while recording the current.

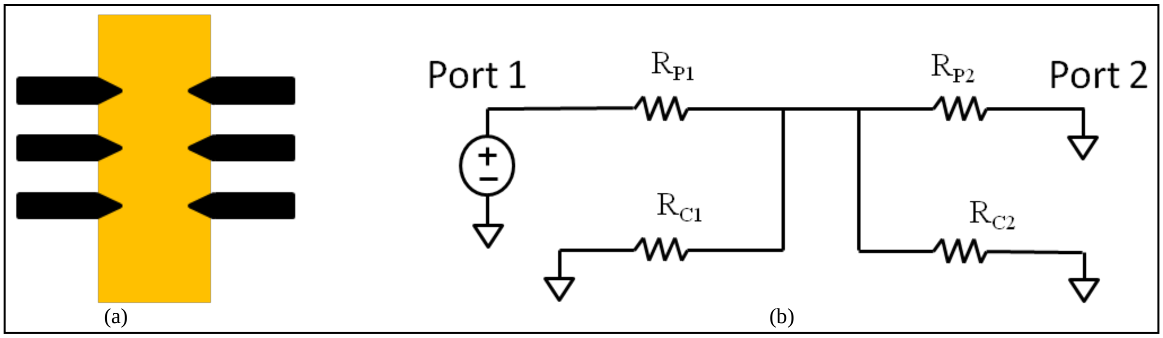

Figure 6. Determination of R4 (a) picture of proper probe placement for shorting all probe tips and (b) circuit diagram for measurement of R4.

There are other options generating the required four equations; however, these are the ones that will be used in the procedure described in this note. It is also possible to make use of the ability to measure current from both ports in the final measurement.

Calculation of Resistances

The equations for each of the measured resistances are shown as follows:

$$R1 = R_{P1} + R_{C1} \tag{1}$$

$$R2 = R_{P2} + R_{C2} \tag{2}$$

$$R3 = R_{P1} + R_{P2} \tag{3}$$

$$R4 = R_{P1} + \frac{1}{\frac{1}{R_{P1}} + \frac{1}{R_{C1}} + \frac{1}{R_{C2}}} \tag{4}$$

When these are solved for the desired transmission line resistances, we find the equations for these to be

$$R_{P1} = \frac{R1\,R3+R2\,R4-R3\,R4 \pm \sqrt{R2\,(R1+R2-R3)\,(R1-R4)\,(R3-R4)}}{R1+R2-R4} \tag{5}$$

$$R_{C1} = \frac{R1^{2}+R1\,R2-R1\,R3-R1\,R4-R2\,R4+R3\,R4 \pm \sqrt{R2\,(R1+R2-R3)\,(R1-R4)\,(R3-R4)}}{R1+R2-R4} \tag{6}$$

$$R_{P2} = \frac{R2\,R3-R2\,R4 \pm \sqrt{R2\,(R1+R2-R3)\,(R1-R4)\,(R3-R4)}}{R1+R2-R4} \tag{7}$$

$$R_{C2} = \frac{R2^{2}+R1\,R2-R2\,R3 \pm \sqrt{R2\,(R1+R2-R3)\,(R1-R4)\,(R3-R4)}}{R1+R2-R4} \tag{8}$$

Procedure for Determining DUT Voltages

Once the transmission line resistances are known, it becomes possible to mathematically determine the voltage on the DUT. Figure 7 shows the circuit diagram of a FET with the transmission line resistances included.

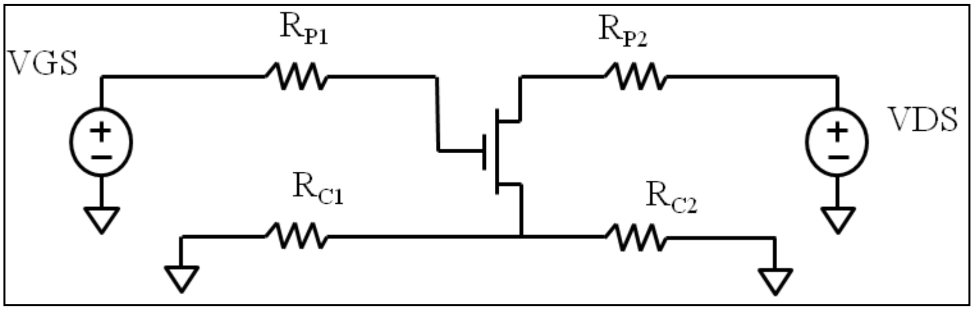

Figure 7. Measurement of FET with transmission line resistances.

In figure 7, it is shown that the voltages on the DUT are given by

$$VGS_{DUT} = VGS_{Source} - I_g\,R_{P1} - \left(I_g+I_d\right)\cdot\left(R_{c1}\|R_{c2}\right) \tag{9}$$

$$VDS_{DUT} = VDS_{Source} - I_d\,R_{P2} - \left(I_g+I_d\right)\cdot\left(R_{c1}\|R_{c2}\right) \tag{10}$$

This produces a set of voltages that are slightly different from the power supply voltages. Current voltage curves are by tradition normally presented as currents dependent on equally spaced voltages. The voltages calculated when accounting for transmission line loss are not equally spaced. It is possible to use interpolation to find the current at the supplied voltage points.

Results

The measurements described were performed on our system with the results as follows:

$$R1 = 5.42\ \Omega$$

$$R2 = 0.92\ \Omega$$

$$R3 = 6.16\ \Omega$$

$$R4 = 0.79\ \Omega$$

Using these values, the following transmission line resistances were calculated:

$$R_{P1} = 5.38\ \Omega$$

$$R_{C1} = 0.04\ \Omega$$

$$R_{P2} = 0.78\ \Omega$$

$$R_{C2} = 0.14\ \Omega$$

Using these values, the DUT voltages for a typical IV curve were calculated in a MATLAB program. The same program interpolated the current to the original power supply voltages. Figure 8 shows a plot of the original measured current and the interpolated current.

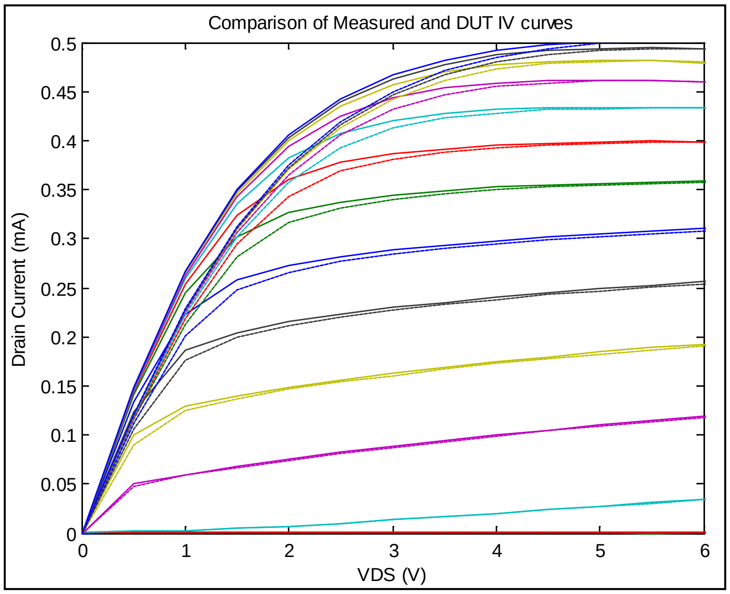

Figure 8. Measured IV curve (dash line) plotted besides calculated.

As is shown in figure 8, there is a non-trivial difference between the measured IV characteristics and the actual IV characteristics of the DUT. This is especially true in the linear (ohmic) region of device operation.

Conclusion

In order to accurately measure and model devices, the effects from the measuring instruments must be taken into account. A procedure for determining and correcting for transmission line resistances between a power supply and a DUT has been presented. MATLAB codes for performing the calculations described are provided in the appendices.

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Appendix A

MATLAB Function for calculating transmission line resistances

```
function [R1p, R1c, R2p, R2c] = Calc_PSupply_Resistances(R1, R2, R3, R4)

% R1 is the resistance of port1 shorted
% R2 is the resistance of port2 shorted
% R3 is the resistance of power line of port one to port 2 when port 2 is
% grounded
% R4 is the resistance of port1 shorted to the common of port 1 and 2 when
% port 1 is
% R1p is the port 1 resistance between the power supply voltage and the DUT
% R1c is the port 1 resistance between the DUT and the power supply common
% R2p is the port 2 resistance between the power supply voltage and the DUT
% R2c is the port 2 resistance between the DUT and the power supply common

Rgp1 = (R1+R2+(-1).*R4).^(-1).*(R1.*R3+(-1).*sqrt(R2.*(R1+R2+(-1).*R3).*( ...
  R1+(-1).*R4).*(R3+(-1).*R4))+R2.*R4+(-1).*R3.*R4);

Rgc1 = (R1+R2+(-1).*R4).^(-1).*(R1.^2+R1.*R2+(-1).*R1.*R3+sqrt(R2.*(R1+ ...
  R2+(-1).*R3).*(R1+(-1).*R4).*(R3+(-1).*R4))+(-1).*R1.*R4+(-1).* ...
  R2.*R4+R3.*R4);

Rdp1 = (R1+R2+(-1).*R4).^(-1).*(R2.*R3+sqrt(R2.*(R1+R2+(-1).*R3).*(R1+( ...
  -1).*R4).*(R3+(-1).*R4))+(-1).*R2.*R4);
Rdc1 = (R1.*R2+R2.^2+(-1).*R2.*R3+(-1).*sqrt(R2.*(R1+R2+(-1).*R3).*(R1+( ...
  -1).*R4).*(R3+(-1).*R4))).*(R1+R2+(-1).*R4).^(-1);
Rdp2 = (-1).*(R1+R2+(-1).*R4).^(-1).*((-1).*R2.*R3+sqrt(R2.*(R1+R2+(-1).* ...
  R3).*(R1+(-1).*R4).*(R3+(-1).*R4))+R2.*R4);
Rgc2=(R1+R2+(-1).*R4).^(-1).*(R1.^2+R1.*(R2+(-1).*R3+(-1).*R4)+(-1).* ...
  sqrt(R2.*(R1+R2+(-1).*R3).*(R1+(-1).*R4).*(R3+(-1).*R4))+(-1).* ...
  R2.*R4+R3.*R4);
Rdc2 = (R1.*R2+R2.^2+(-1).*R2.*R3+sqrt(R2.*(R1+R2+(-1).*R3).*(R1+(-1).* ...
  R4).*(R3+(-1).*R4))).*(R1+R2+(-1).*R4).^(-1);
Rgp2 = (R1+R2+(-1).*R4).^(-1).*(R1.*R3+sqrt(R2.*(R1+R2+(-1).*R3).*(R1+( ...
  -1).*R4).*(R3+(-1).*R4))+R2.*R4+(-1).*R3.*R4);;

if Rdp1>0&&Rgc1>0&&Rdc1>0&&Rgp1>0
    R1p = Rgp1;
    R1c = Rgc1;
    R2p = Rdp1;
    R2c = Rdc1;
else
    R1p = Rgp2;
    R1c = Rgc2;
    R2p = Rdp2;
    R2c = Rdc2;
end
```

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Appendix B

MATLAB Function for determining DUT IV Characteristics given

```
function [IDSp1, VGSp, VDSp] = Deembed_PSupply_Resistances(IDS, IGS, VDS,
VGS, Rgp, Rgc, Rdp, Rdc)

% Rgp is the gate power Resistance
% Rgc is the gate common Resistance
% Rdp is the drain power Resistance
% Rdc is the drain common Resistance
% IDSp1 is the current when the DUT is biased at VDS and VGS
% VGSp is the gate voltage on the DUT with IDS current
% VDSp is the drain voltage on the DUT with IDS current

[r c] = size(IDS);

if r ~= length(VDS)
    IDS = IDS';
    c = r;
    r = length(VDS);
end

VGS_mesh=VGS;
for ii = 2:r
    VGS_mesh = [VGS_mesh;VGS];
end

VDS_mesh=VDS;
for ii = 2:c
    VDS_mesh = [VDS_mesh VDS];
end


Rg = Rgp;
Rd = Rdp;
Rs = 1/(1/Rgc + 1/Rdc );


Vs = (IDS+IGS)*Rs;

VGSp = VGS_mesh - IGS*Rg - Vs;
VDSp = VDS_mesh - IDS*Rd - Vs;
IDSp1 = griddata(VGSp,VDSp,IDS,VGS_mesh,VDS_mesh,'v4');
% % Uncomment to surface plot IV curves
% figure;
contour3(VGSp,VDSp,IDS,[0:.05:.5]);hold;contour3(VGS_mesh,VDS_mesh,IDSp1,[0:.
05:.5],'--');
% contour3(VGS_mesh,VDS_mesh,IDS,[0:.05:.5],':');
```

List of Symbols, Abbreviations, and Acronyms

BJT	bipolar junction transistor
DC	direct current
DUT	device under test
GSG	ground-signal-ground
HEMT	high electron mobility transistor
MOSFET	metal oxide semiconductor field effect transistor
R_P	power resistance
R_C	common resistance
TRL	thru-reflect-line

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