Methods to test discrete semiconductors in 1149.4 environment

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Abstract—This paper describes methods of testing discrete semiconductors in the environment defined by the IEEE 1149.4 standard for a mixed-signal bus. First, measurement procedures for obtaining central electrical parameters of diodes and transistors are introduced and illustrated. Then, the procedures are carried out and the achieved measurement results presented. It was found that testing and measuring some of the electrical parameters of discrete semiconductors is possible in the 1149.4 environment. These parameters allow the determination of whether the component under test is working properly or not. Also discussed are limitations of the 1149.4 environment in discrete semiconductor testing.

Keywords – 1149.4, Analog boundary scan, discrete semiconductors

I. INTRODUCTION

HAVING been developed to resolve problems encountered in traditional testing of mixed-signal boards, the IEEE 1149.4 Standard for a Mixed-Signal Test Bus [1] presents methods of testing mixed-signal boards when test point access is difficult or even impossible with traditional methods. Most studies on the 1149.4 focus on testing passive components [3,4,6] as well as monitoring and routing signals [5,7,8]. The main chip in these studies has been the STA400, a general purpose 1149.4 IC, [2] and the used measurement equipment has been fairly inexpensive.

This paper presents methods for testing discrete active components, such as diodes and transistors, in the 1149.4 environment, using a test circuit similar that shown in [4], where the main component is the STA400 chip. All tests are carried out with DC voltages and the results can be used to ascertain whether the component under test is working properly in conformity with its electrical parameters.

The rest of the paper is organized as follows. Section II introduces the applied measurement methods and Section III shows experimental results and provides a discussion on them. Finally, Section IV presents the conclusions.

II. THE MEASUREMENT METHODS

Table I, which shows important parameters of discrete semiconductors, is partly adopted from [9]. Characterizing some of these parameters, such as $V_{BR}$, necessitates the application of high test voltages, which are impossible to produce in the 1149.4 environment. Additionally, some tests may require too high current values. On the other hand, very small currents, such as leakage currents, are also impossible to measure due to the leakage currents of the STA400 chip itself. Hence, all tests on discrete components were performed within the voltage and the current ranges of the STA400.

Fig. 1 shows the test circuitry for single component measurements, adopted from [4]. However, only some of the pins and analog boundary modules (ABM) of the STA400 are shown here. In this circuit, the sense resistor $R_s$ is connected between the two analog pins of the STA400 and the component under test is connected to two or three other analog pins, depending on component’s pin count. Stimuli to the analog pin AT1 are produced by connecting the signal source to $R_s$, whose other end, in turn, is connected to AT1.

An equivalent circuit is shown for every measurement procedure. In the equivalent circuits, $R_{sw}$, $R_{gnd}$ and $R_{vh}$ represent the path resistances of the STA400, which vary by the current and voltage ranges.

A. Diode measurements

Table I presents the most important parameters for diodes, together with additional parameters for Zener diodes. Some of these parameters are not measurable in the 1149.4 environment due to the voltage restrictions of the STA400.
For example, the reverse breakdown voltage usually requires more than 50 V. On the other hand, testing $V_{BR}$ is pointless exercise, as it may permanently damage the component under test.

Of the diode’s characteristics, the most informative are the forward voltage level and the possible breakdown voltage level, which make it easy to identify the right diode type. Other interesting characteristics of breakdown diodes are the leakage current and dynamic impedance. There are two methods of testing a diode’s voltage levels and currents with the STA400: the first one involves using an external signal source and the other using the STA400’s own voltage high, or logical ‘1’, control on the ABM. An external signal source enables the characterization of the diode’s voltage-current by allowing the signal source to be swept within its operating voltage range. In contrast, applying logic ‘1’ on the ABM only allows the use of one voltage level, namely, the operation voltage.

Characterizing the voltage-current curve of diodes is done as follows. First, the signal source is connected to AT1 through $R_s$ as in Fig. 1. Next, the signal is routed through AB1 to the anode of the diode in ABM3, while the cathode of the diode is grounded in ABM4. Fig.2.a shows the equivalent circuit of the measurement. The signal source is swept from 0 V to the operating voltage, which is usually 5 V. At every voltage step, voltages are measured with a meter connected through AT2 to AB2. First, the voltages of ABM1 (U1) and ABM2 (U2) are measured for current calculation, whereafter the voltages of ABM3 (U3) and ABM4 (U4) are measured to obtain the voltage across the diode. After the first sweep, the configuration is changed such that ABM4 is now connected to AB1 and ABM3 is grounded, which gives the possibility to measure the diode’s reverse voltage properties.

Testing diodes by using logic ‘1’ on the ABM is done as follows. Initially, the signal source is set either to 0 V or to ground level, and the diode is connected from ABM3 to ABM4 as in Fig. 1. The equivalent circuit of the measurement is shown in Fig.2.a. When measuring forward voltage properties, ABM3 is set to logic ‘1’. Then, the test signal is routed through the diode to ABM4 and further to AT1 through $R_s$. whose other end is connected to ground through ABM1. The voltage across the diode is measured from ABM3 (U1) and ABM4 (U4) through AB2, and the current is calculated from the value of $R_s$ and the measured voltage values at ABM2 (U3) and ABM1 (U2), which are also measured through AB2. The reverse voltage properties are measured in the same way, but ABM4 is set to logical ‘1’ and ABM3 is connected to AB1.

B. Bipolar transistor measurements

As a rule, testing discrete components only requires signal busses for the source and measurement signals. Since typical bipolar transistors have three connectors, some tests call for the use of three busses to route two source signals and a measurement signal. This complicates or even precludes the application of certain tests in the 1149.4 environment. Possible resistors that are already present on the DUT may be useful when testing some transistor parameters.

Another problem with bipolar transistors is that they are defined for quite large current values. For example, the saturation voltage ($V_{CE(sat)}$) is usually defined for a base current of 10 mA and a collector current of 100 mA. However, the current going through analog busses in the STA400 is invariably less than 3 mA.

Although the following measurement procedures are made for npn transistors, they are easily adaptable to pnp transistors.

1) DC current gain measurement

To indicate the operation of the transistor, one can use the DC current gain (hFE) test. hFE is the common emitter current gain for large signals and is defined as follows:

$$h_{FE} = \frac{I_C}{I_B},$$

where $I_C$ is the collector current, $I_B$ the base current and $I_E$ the emitter current. hFE is usually determined for specified $I_C$ and collector/emitter voltage ($V_{CE}$) levels. Its value tends to vary considerably from transistor to transistor.

Fig. 3.a shows the equivalent circuit for $h_{FE}$ testing. The collector of the transistor is connected to high voltage in ABM3. From the function generator, the DC signal is routed through $R_s$ to AT1 before passing through AB1 to ABM4, where it is connected to the transistor’s base. The emitter of the transistor is connected to ABM5, which is used only for probing. In addition, the emitter is connected to known resistor $R_t$, which is needed for $I_E$ measurements. $R_t$ may be an already existing resistor in a DUT.

![Fig. 1 Test circuit for single component testing.](image1)

![Fig. 2. Equivalent circuits for testing a diode by the current-voltage characterization method (a) and the high voltage method (b).](image2)
First, the function generator’s voltage level is swept to a level when the $V_{CE}$ is equal or under 1V. The voltage is measured from the voltages recorded at ABM3 ($U_3$ in Fig. 3.a) and ABM5 ($U_5$). When $V_{CE}$ reaches the desired level, the corresponding voltage levels at ABM1 ($U_1$) and ABM2 ($U_2$) are measured through AB2 to obtain $I_B$. Then, to get $V_{BE}$ also the voltage at ABM4 ($U_3$) is measured. Finally, $I_E$ is calculated from the value of $R_1$ and from the voltage level at ABM5.

2) Base-emitter voltage measurement

In component data sheets, the base-emitter voltage ($V_{BE}$) is defined as the voltage from the base to the collector when the collector current ($I_C$) and collector-emitter voltage ($V_{CE}$) are at defined levels. Usually, $I_C$ is defined as 100 mA and $V_{CE}$ as 1V. $V_{BE}$ depends on $I_C$ such that the bigger the $I_C$, the bigger the $V_{BE}$.

To measure $V_{BE}$, one may use a circuit similar to that in the current gain measurement. But in the absence of an external resistor $R_1$ in the testable circuit, $V_{BE}$ can only be measured when the emitter is connected to ground. In this situation, however, the current from the collector and emitter is unknown. Nevertheless, its value can be estimated from the maximum output current of the ABM when it is connected to high voltage. The maximum output current of the ABM is less than 2.5 mA.

Measuring $V_{BE}$ resembles the current-voltage characterization of diodes. First, the function generator is connected through $R_S$ to AB1, and further to the transistor’s base. The collector is connected to high voltage through ABM3, and the emitter is connected to ground through ABM5.

The function generator is swept from 0 V to $V_{CC}$. At every voltage level, voltages are measured at ABM1 ($U_1$) and ABM2 ($U_2$) through AB2 to obtain the base current ($I_B$). Moreover, voltages at ABM4 ($U_3$) and ABM5 ($U_5$) are measured to get $V_{BE}$. Then, to obtain $V_{CE}$, also the voltage at ABM3 ($U_3$) is measured. The value of $V_{BE}$ is defined when $V_{CE}$ reaches the desired level, such as 1 V.

3) Collector-emitter saturation voltage measurement

The collector-emitter saturation voltage ($V_{CE(sat)}$) is measured with a circuit similar to that of the $h_{FE}$ measurement. $V_{CE(sat)}$ is usually defined as the voltage over the collector and emitter when the collector current ($I_C$) is ten times larger than the base current ($I_B$). Generally, $I_C$ is set at 100 mA, which is too high for the 1149.4 environment.

When using the circuit shown in Fig. 3.a, the currents must be calculated such that the emitter current ($I_E$) is the sum of $I_C$ and $I_B$. As a result, $I_E$ must be eleven times larger than $I_B$. The measurement procedure is similar to the $h_{FE}$ measurement, the only difference being that the signal generator is driven from 0 to $V_{CC}$. The currents are measured and when the current ratio reaches the desired ratio of 11:1, $V_{CE}$ is determined.

C. Field effect transistor (FET) measurements

Table I presents some important FET parameters. One of the most interesting among these is transconductance ($g_m$), but it cannot be measured in the 1149.4 environment without a large number of additional components. Thus, transconductance measurements require two more signal busses and extra capacitors for dc-blocking. Also leakage currents are impossible to measure due to the leakage currents of the 1149.4 bus. The following measurements enable one to test some FET parameters which then allows the determination of whether the component works properly or not. The following procedures are for an n-type MOSFET transistor, but are also easily adaptable to other types of FET.

1) Gate threshold voltage measurement

Information as to how high a voltage is needed to turn a channel on or off is given by the gate threshold voltage ($V_{GS(th)}$). Technical datasheets for transistors usually provide a value for $V_{GS(th)}$, which is obtained when the drain-source voltage equals the gate-source voltage at the exact drain current level.

The measurement procedure is as follows. The signal from the function generator is routed through $R_s$ to AT1. AT1 is connected to AB1, which is connected to the drain of the
transistor through ABM3 and to the gate through ABM4. ABM5 is used to connect the transistor’s source to ground. Fig. 4.a shows the equivalent circuit.

The function generator is swept from 0 to \( V_{cc} \). At every step, the voltage is measured at ABM1 (\( U_1 \)) and ABM2 (\( U_2 \)) to record the current going to the drain and gate. Because the gate current (\( I_G \)) is negligible, it can be assumed that the current flowing through is \( I_D \). Also the voltages at ABM3 (\( U_4 \)), ABM4 (\( U_3 \)) and ABM5 (\( U_5 \)) are measured to get actual values for \( V_{DS} \) and \( V_{GS} \). \( V_{GS(th)} \) is defined when \( I_D \) reaches the level stated in the technical datasheet.

2) Drain-Source resistance measurement

Drain-Source resistance (\( r_{DS(on)} \)) is the switch resistance of the FET when it is on. Since this resistance tends to be small, the measurement is very difficult to perform. In this study, the measurement procedure is as follows. As usual, the signal from the function generator is connected through \( R_S \) to AB1. From AB1, the signal goes to the drain of the transistor. The transistor’s gate is connected to high voltage through ABM4 and the source is connected to ground through ABM5. Fig 4.b shows the equivalent circuit of the connection.

Voltages are measured at ABM1 (\( U_1 \)) and ABM2 (\( U_2 \)) to obtain the drain current (\( I_D \)) and at ABM3 (\( U_3 \)) and ABM5 (\( U_5 \)) to get \( V_{DS} \). Also the voltage at ABM4 (\( U_4 \)) is measured to establish \( V_{GS} \). Having acquired \( V_{DS} \) and \( I_D \), one can calculate \( r_{DS(on)} \).

III. MEASUREMENT RESULTS AND DISCUSSION

The measurement system shown in Fig. 1 was built using an Agilent 33120A as function generator and an Agilent 34401A as voltmeter. For boundary scan control, we used a JTAG PM3705 boundary-scan controller. The measurement equipment was controlled by LabVIEW software.

A. Diode measurements

Diodes were measured as described in Section II. As Table II indicates, a number of different types of diode were tested. Among these, the first three were LEDs, bat48 and bat85 were Schottky diodes, 1n914 was a regular pn-junction diode and the last three were Zener diodes. In the table, the first two columns represent the voltage values \( V_F \) and \( V_Z \) using the voltage high control on the STA400. The middle columns represent measurement results obtained using the voltage-current characterization method. The last column presents reference measurements of the diodes. The reference measurements were done with the same current values as the 1149.4 measurements.

Table II illustrates that the voltage-current characterization method and voltage high method produce essentially the same results. However, some voltage levels differ slightly, because the currents did not match exactly in every measurement. This minor discrepancy is explained by the fact that the voltage high method produced somewhat larger currents. Also both of the 1149.4 measurement methods produced similar results which were obtained from the reference results.

Fig. 5. presents the voltage-current characteristics of the measured Zener diodes. In this measurement, the step size of the voltage sweeps was 0.1 V and the size of \( R_S \) was about 1 k\( \Omega \). It can be seen that the maximum current passing through
the diode was approximately 1.5 mA. As shown in the equivalent circuit of the measurement (Fig. 2.a), this current is limited by the Rs and switch resistances (Rsw) of the STA400, and explains why currents in the breakdown region are smaller with higher voltage Zeners.

The Zener diode zte2 was measured with four different sense resistors, and the Rs value was varied by decade steps from 0.1 to 100 kΩ. Fig. 6 shows the measured minimum and maximum current and voltage values. All the values shown are absolute. As can be seen from the figure, a large sense resistor has a stronger effect on current than on voltage. Thus, by allowing the use of larger currents, a small Rs is better suited for more accurate measurements of diode behaviour in the breakdown region.

Despite voltage and current restrictions, the mixed-signal test bus can be used for diode measurements. With the thus acquired information, one may tell whether the diode under test is mounted appropriately and working properly.

B. Bipolar transistor measurements

1) DC current gain measurement

Six identical BC337 transistors were used in the DC current gain (hFE) measurements. In Table III, the first column presents the reference measurements for hFE, in which VCE was forced to 1 V and IE to 2 mA. In the 1149.4 measurement, whose results are given in the second column in Table III, was about 2 mA.

Measuring VCE(sat) is difficult, because the ABM’s maximum output current is limited by the Rs and switch resistances (Rsw) of the STA400, and explains why currents in the breakdown region are smaller with higher voltage Zeners.

The presented method for hFE measurements in the 1149.4 environment is valid for small current ranges, whereas measurements with larger currents are restricted by the ABM’s maximum output current. Also the value of Rs greatly affects the measurement by resisting IE and the already small IB.

As shown, the accuracy rate of the results in the 1149.4 measurements is within 3 % of the reference measurements. There are many reasons for the errors in the results. Firstly, the measurement conditions (VCE an IE) were not exactly the same and, secondly, measurements with small IE values were affected by the leakage currents of the STA400.

The measurement results obtained in the 1149.4 measurement is at the most 1.6%. Because the error in the measurement method is the main reason for the error in the measurement results.

3) Collector-emitter saturation voltage measurement

Saturation voltages are generally measured when the collector current, usually about 100 mA, is ten times bigger than the base current. Using the circuit for VCE(sat) measurements described in Chapter II brought out the limitations of the ABM’s maximum output current. To get the required 11:1 current level ratio, a large resistor had to be attached to the transistor’s emitter. Accurate measurements of IB also required the application of a fairly large resistor as Rs.

In the BC337 measurements, the emitter resistance value was 830 kΩ and Rs was 50 kΩ. Getting the right ratio between IB and IE means that only the emitter’s resistance value has an effect on the results. According to the BC337 data sheets, VCE(sat) is defined as less than 700 mV, when IB is 500 mA and IE is 50 mA. In our measurements, VCE(sat) was 480 mV, when IB was 5.5μA and IE 520 nA.

Measuring VCE(sat) is difficult, because the ABM’s maximum current is small and the resistance in the emitter must be specified for the measurement. As a result, this measurement method is possible only when the Rs value is sufficiently large.

C. Field effect transistor (FET) measurements

1) Gate threshold voltage measurement

Characterizing the gate threshold voltage (VGS(th)) was similar to the current-voltage characterization of diodes. Thus, VGS was measured as a function of drain current (ID) using six 2n7000 transistors. For the reference measurements in Table IV, VGS(th) was defined when ID was 1 mA. This same ID value was also used in the 1149.4 measurement to define VGS(th).

The size of RS in the 1149.4 measurement was 1 kΩ. VGS(th) characterization would not have been possible with higher Rs values, because the required current would have been too small. With 1 kΩ, the maximum current was just over 1 mA. The measurement results obtained in the 1149.4 measurement system varied only by 0.2% relative to the reference measurements.
2) Drain-Source resistance measurement

Drain-Source resistance ($r_{DS(on)}$) is usually defined for large currents than are impossible to measure with the STA400. For example, in the datasheet for the 2n7000, $r_{DS(on)}$ is defined when $I_D = 50$ mA and $V_{GS} = 5$ V. The reference measurements shown in Table IV were performed using an $I_D$ of 400 μA and a $V_{GS}$ of 5 V. These reference values were chosen to be similar to those in the 1149.4 measurement.

Usually, $r_{DS(on)}$ is small; for the 2n7000, the maximum resistance is 7.5 Ω. A larger current eases the measurement, because 50 mA produces a voltage of 375 mV over the channel when $r_{DS(on)}$ is 7.5 Ω. Contrastingly, a 1 mA current produces a voltage of only 7.5 mV, which is difficult to distinguish from the leakage currents of the STA400. For the current measurement, $R_S$ was chosen to be 10 kΩ when $I_D$ is 400 μA. Had $R_S$ been smaller, such as 1 kΩ, $I_D$ would have been bigger. A bigger $I_D$ raises the ground resistance of the ABM, causing the voltage level in the transistor’s source to rise. When the source has a higher potential than the ground, $V_{GS}$ becomes smaller and that changes the measurement conditions. It was tested with the STA400 that when $I_D$ is 1 mA, $V_{GS}$ is reduced to 3.75 V. In reference measurements, when $V_{GS}$ was 3.75 V and $I_D$ 1 mA, $r_{DS(on)}$ was 3.8 Ω. Fig. 7. shows the effect of $I_D$ on $V_{GS}$ and the measurement of $r_{DS(on)}$ in the 1149.4 environment.

The values for $r_{DS1}$ in Table IV are the ones used in the measurement procedure presented in Section II, while the values for $r_{DS2}$ are those for a similar measurement procedure, except that the source of the transistor was connected to actual ground. As the results indicate, the values of $r_{DS2}$ differ only by 12 % from the reference values, whereas those of $r_{DS1}$ differ by almost 60 %. The measurement error is partly caused by the lower $V_{GS}$ and partly by the leakage currents of the STA400.

### Table IV

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