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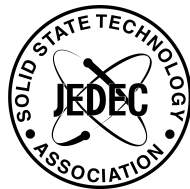
Procedure for the Wafer-Level Testing of Thin Dielectrics

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JEDEC Solid State technology Association



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PROCEDURE FOR THE WAFER-LEVEL TESTING OF THIN DIELECTRICS

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PROCEDURE FOR THE WAFER-LEVEL TESTING OF THIN DIELECTRICS

Foreword

This document is intended for use in the MOS Integrated Circuit manufacturing industry fabrication processing and test and describes procedures developed for estimating the overall integrity of thin oxides. Three basic test procedures are described, the Voltage-Ramp (V-Ramp), the Current-Ramp (J-Ramp) and the Constant Current (Bounded J-Ramp) test. Each test is designed for simplicity, speed and ease of use.

The purpose of this document is to describe oxide test techniques for quick evaluation and control of oxide fabrication techniques. It does not specify acceptance or rejection criteria for any of the described procedures and therefore not intended to be used to predict MOS Integrated Circuit failure rates.

The material contained within this publication is formulated under the cognizance of JEDEC JC-14.2 Committee and approved by the JEDEC Board of Directors.

PROCEDURE FOR THE WAFER-LEVEL TESTING OF THIN DIELECTRICS

(From JEDEC Board Ballot JCB-99-24, formulated under the cognizance of JEDEC JC-14.2 Subcommittee on Wafer Level Reliability)

1 Scope

This document defines test procedures for the V-Ramp, J-Ramp and the Bounded J-Ramp oxide integrity tests. Included within this document are recommended data analysis methods and guidelines for statistical sampling.

2 Introduction

2.1 Overview

The thin dielectric integrity of MOS devices and circuits is an important reliability concern. Historically, thin oxide reliability has been driven by oxide defects. In general the intrinsic oxide lifetime is much longer than the use requirements, but defects can significantly reduce oxide lifetime. The procedures described herein were developed to estimate the integrity of a thin oxide and as a tool for driving constant improvement in the thin oxide process.

The test procedures described within this document should not be used to predict failure rates of a semiconductor product but rather tools for process control of oxide integrity. In actual practice the oxide reliability of a semiconductor product is a complicated function of individual transistor duty cycles, transient voltage variation, the gate graded potential and series resistance in the gate load. These parameters are not considered within this document.

2.2 Choosing the appropriate stress procedures

Three test procedures are described within this document; a ramped voltage (V-Ramp), a ramped current (J-Ramp) and a constant current (Bounded J-Ramp) test. Each of these procedures is designed for simplicity, speed and ease of use and can be implemented at each point in the process from oxide formation onward.

The voltage ramp test (V-Ramp) starts at the use condition voltage or lower and ramps linearly from this value until oxide breakdown. The current density ramp test (J-Ramp) begins at a low value of current and ramps exponentially until oxide breakdown. The constant current test (Bounded J-Ramp) only rises to a specified current density level and it is maintained there until oxide breakdown.

2 Introduction (cont'd)

2.2 Choosing the appropriate stress procedures (cont'd)

V-Ramp tests are often applied to oxides where characterization of the defects at lower electric fields is important. On the other hand, since the J-Ramp begins at a voltage sufficient to produce measurable amounts of tunneling current (typically much higher than the starting voltage for a V-Ramp test), it can provide only very coarse segregation of the low field breakdowns, but can provide fine segregation of the high field breakdowns in much less time than a V-Ramp test. J-Ramp tests are often applied to small area test structures as a means of controlling an established process.

The Bounded J-Ramp (constant current) provides a very repeatable charge-to-breakdown (Q_{bd}) measurement where the current/current density is ramped to a specified level and then held until breakdown. The majority of the charge-to-breakdown in both the J-ramp and V-ramp tests occurs during the last few steps of testing. Thus timing, measurement conditions, step size can greatly influence the value of Q_{bd} using these tests. With the bounded J-Ramp, once a constant current value is reached, each increment contributes approximately the same charge to the total value of Q_{bd} reducing the dependence on testing equipment. For these reasons, comparisons of Q_{bd} should be performed using the Bounded J-Ramp.

As a result of this difference in the speed and field resolution of the above tests, there are applications where each one might be more appropriate. The J-Ramp test typically takes less time to determine defect density than a V-Ramp test. So the J-Ramp might be favored if large sample size and throughput are important. The Bounded J-Ramp has better Q_{bd} resolution. When low field extrinsic information is desired, then the V-Ramp may be a better choice. However, all of these tests will allow resolution between defective (extrinsic) and non-defective (intrinsic) oxide test structures.

3 Terms and definitions

The following symbols are used in this document. They have been listed alphabetically for the convenience of the reader.

a_{oxide} (cm^2): Thin oxide gate area.

compliance: The test equipment maximum current or voltage forcing capability. Often the user can specify a compliance limit for a particular test. In this case the test instrumentation will not exceed this compliance limit during the test procedure.

3 Terms and definitions (cont'd)

E (V/cm): E is the estimated oxide electric field. The general formula for E is:

$$E = V / T_{\text{ox}},$$

where V is the voltage and T_{ox} is the estimated oxide thickness, as determined by a consistent, documented method. The method (or a reference to the documented standard) must be included in the data report.

E_{bd} (V/cm): The estimated oxide electric field just prior to the detection of breakdown (see Annex C).

J (A/cm²): The oxide current density calculated by dividing the oxide current by the oxide area (A_{oxide}).

Q_{bd} (Coulombs): The accumulated charge passing through the oxide prior to breakdown is defined as:

$$Q_{bd} = \int_{t=0}^{t=t_{bd}} I(t) dt \quad (2)$$

where t is time. The Q_{bd} is calculated as the integral from $t = 0$ to $t = t_{bd}$ where t_{bd} is the last measurement time at the step just prior to breakdown.

q_{bd} (C/cm²): The accumulated charge density, passing through the oxide at the detection of breakdown. Calculated as:

$$q_{qb} = \frac{Q_{bd}}{A_{\text{oxide}}} \quad (3)$$

4 V-ramp test procedure

4.1 Test configuration

The voltage-ramp (V-RAMP) test is performed on an oxide capacitor by applying a voltage between the gate electrode (typically polysilicon or aluminum) and bulk electrode (typically substrate or well) with all other diffusions and wells connected to substrate. It is recommended that the gate voltage polarity should bias the device into accumulation to minimize inversion capacitance effects but inversion can be used if the test structure design or conditions such as heat or light illumination provides a source of minority carriers to the inverted layer. Although these procedures are applicable to measurements at other operating temperatures these procedures are typically performed at room temperature (25 ± 5 °C).

The oxide capacitor test structure should be designed so that parasitic series resistance effects are minimized. High series resistance can severely impact the accuracy of these measurements. This is especially true for high current oxide breakdowns where large series resistance voltage drops occur. A second requirement of the capacitor test structure is that probe pads should not exist over the oxide under stress. Mechanical stress caused by probing pads over oxides can result in device damage and inaccurate defect density measurements.

The following sections describe the details of the V-Ramp measurement. This measurement is performed in three parts. First, a pre-oxide current test checks for an ‘initial’ failure. After this test, a voltage ramp is performed until oxide breakdown. Finally a post oxide current test determines the final state of the oxide structure.

4.2 V-Ramp input and output parameters

The V-Ramp input and output parameters are listed in Table 4.1 and Table 4.2, respectively. Table 4.1 defines the input parameters required to set up the V-Ramp test and also defines input parameter guidelines. Table 4.2 defines the V-Ramp output parameters. Optional output parameters include V_{crit} and V_{box} (see Table 4.2 for definitions).

4.2 V-Ramp input and output parameters (cont'd)

Table 4.1 — Input parameters for the V-Ramp test procedure

Input	Units	Comments
V_{use}	V	Oxide voltage under normal operating conditions, typically the power supply voltage of the process. This voltage is used to measure pre- and post voltage ramp oxide current.
I_{init}	A	Oxide breakdown failure current when biased at V_{use} . Typical value is $10\mu\text{A}/\text{cm}^2$ and may change depending on oxide area. For maximum sensitivity the specified value should be well above the worse case oxide current of a "good" oxide and well above the "noise level" of the measurement system. Higher values must be specified for ultra-thin oxides because of direct tunneling effects.
V_{start}	V	Starting voltage for voltage ramp. Typical value is V_{use} .
V_{step}	V	Voltage ramp step height. This value has a maximum value of 0.1 MV/cm. For example, the maximum value can be calculated using $T_{ox} * 0.1 \text{ MV/cm}$, where T_{ox} is in units of centimeters. This is 0.1 V for a 10 nm oxide.
t_{step}	s	Voltage ramp step time. The Voltage ramp step time is determined from the Ramp-rate and V_{step} . The step time should be less than or equal to 0.1sec.
Ramp-rate	V/s	The Ramp-rate is specified at 1.0 MV/cm per second. For example, the ramp-rate should be set to $T_{ox} * 1.0 \text{ MV/cm-sec}$ where T_{ox} is in centimeters. This is 1 V/s for a 10.0 nm oxide.
I_{crit}	A	At least 10 times the test system current measurement noise floor. This oxide current is the minimum value used in determining the change of slope breakdown criteria
I_{box}	A	An optional measured current level for which a stress voltage is recorded. This value provides an additional point on the current-voltage curve. A typical value is 1 μA .
I_{bd}	A	Oxide current breakdown criteria. I_{bd} is obtained from I-V curves and is the oxide current at the step just prior to breakdown.
q_{max}	C/cm^2	Maximum accumulated oxide charge per oxide area. Used to terminate a test where breakdown occurred but was not detected during the test.
V_{max}	V	The maximum voltage limit for the voltage ramp. This limit is specified at 30 MV/cm for oxides less than 20 nm thick and 15 MV/cm for thicker oxides. For example, V_{max} can be estimated from $T_{ox} * 30 \text{ MV/cm}$ where T_{ox} is in centimeters. This is 35 V for a 10.0 nm oxide.

4.2 V-Ramp input and output parameters (cont'd)

Table 4.2 — Output parameters for the V-Ramp test procedure

Outputs	Units	Comments
$I_{\text{use-pre}}$	A	Measured voltage ramp oxide current at V_{use} prior to starting the ramp.
Q_{bd}	C	Charge-to-breakdown. Cumulative charge passing through the oxide prior to breakdown.
V_{crit}	V	Applied voltage at the step where the oxide current exceeds I_{crit} .
V_{box}	V	Applied voltage at the step where the oxide current exceeds I_{box} .
V_{bd}	V	Applied voltage at the step just before oxide breakdown
q_{bd}	C/cm ²	Charge-to-breakdown density.
$I_{\text{use-post}}$	A	Oxide current at V_{use} after the ramp.
Failure Type	-	Failure type as determined in Table 4.3.

4.3 Pre-Ramp oxide current test

Figure 4.1 displays a basic V-Ramp flow diagram. The V-Ramp test procedure begins by performing an oxide current measurement to validate the low field performance of the test device. This test applies a gate bias V_{use} and measures the oxide current $I_{\text{use-pre}}$. If $I_{\text{use-pre}}$ exceeds the fail current (I_{init}) the oxide is considered an ‘initial’ failure (see 4.5 for failure categories) and testing terminates. Figure 4.2 shows a more detailed V-Ramp flow diagram to aid coding the procedure in software.

4.4 Ramp voltage stress

After the pre-test a linear or stepped voltage ramp is applied to the oxide test device. The voltage starts at V_{start} and ramps at a predefined ramp rate, or is stepped by the voltage V_{step} for duration t_{step} . During the voltage ramp the current is monitored at least as often as t_{step} . For the stepped voltage ramp the current measurement should be delayed at each voltage step to allow displacement currents to settle. This implies that t_{step} must be longer than the instrument’s settling time plus the measurement time of the test system. At each voltage step the measured oxide current should be compared to the oxide breakdown criterion. If oxide breakdown has not occurred, the accumulated oxide charge should be recalculated using Equation 4 below:

$$Q_{\text{bd}} = \sum_{i=1}^{i=n} I_{\text{meas}}(i) * t_{\text{step}} \quad (4)$$

where $I_{\text{meas}}(i)$ is the measured oxide current at each voltage step n , t_{step} is the step duration and n the total number of voltage steps just prior to breakdown. If oxide breakdown has been detected, the voltage ramp should be stopped and the final post-ramp device test performed (see 4.5). Figure 4.3 illustrates a typical voltage ramp test.

4.4 Ramp voltage stress (cont'd)

Other test conditions besides oxide breakdown may stop the voltage ramp test. These include reaching the maximum specified test voltage $V_{\max}$, current compliance of test system, or exceeding the maximum specified oxide charge density $q_{\max}$. If either of these conditions occur, a measurement or test condition problem may exist (e.g. improper contact to the gate/bulk, high series resistance, or invalid specified $V_{\max}$ or $q_{\max}$ values).

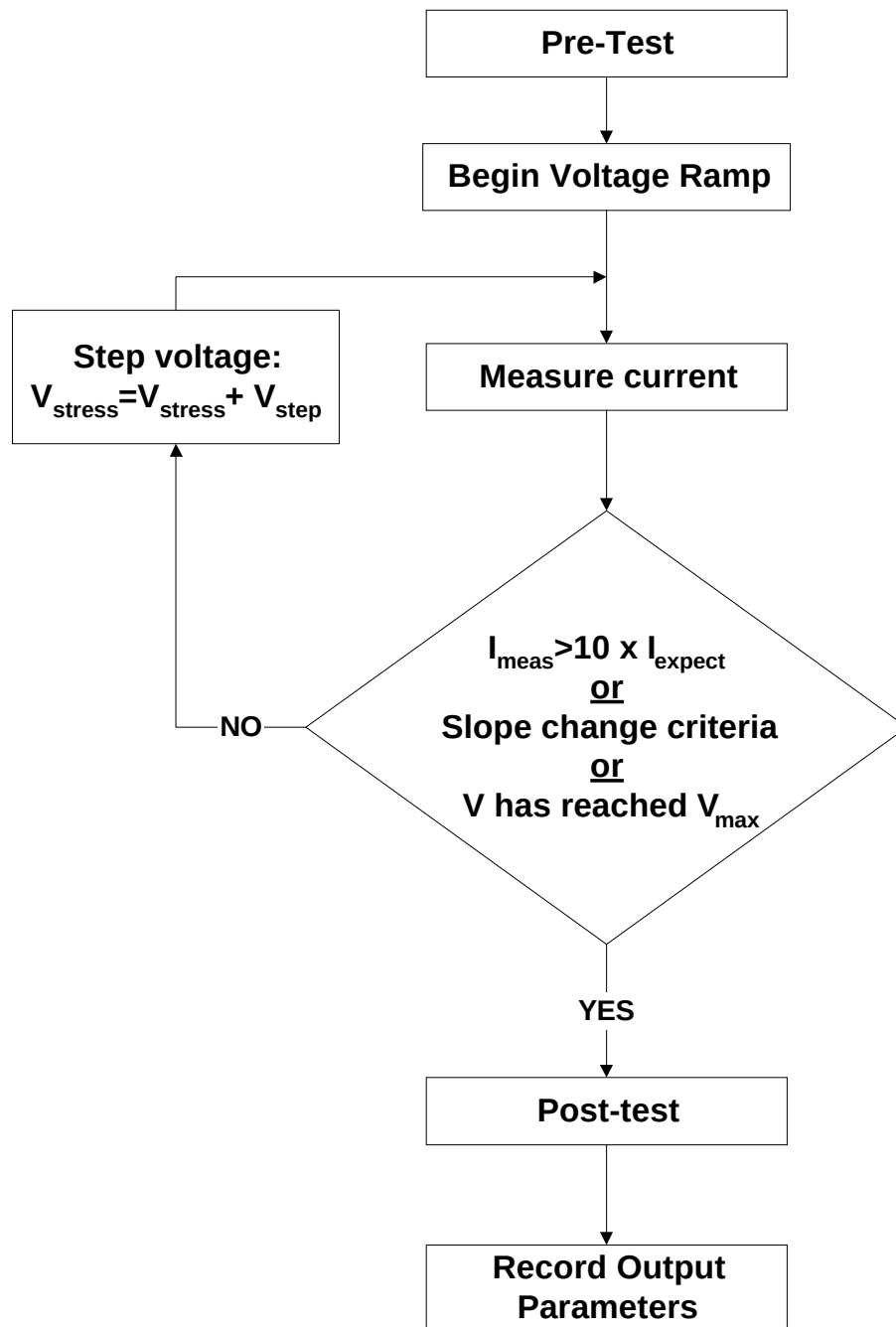


Figure 4.1 — Basic voltage-ramp flow diagram

4.4 Ramp voltage stress (cont'd)

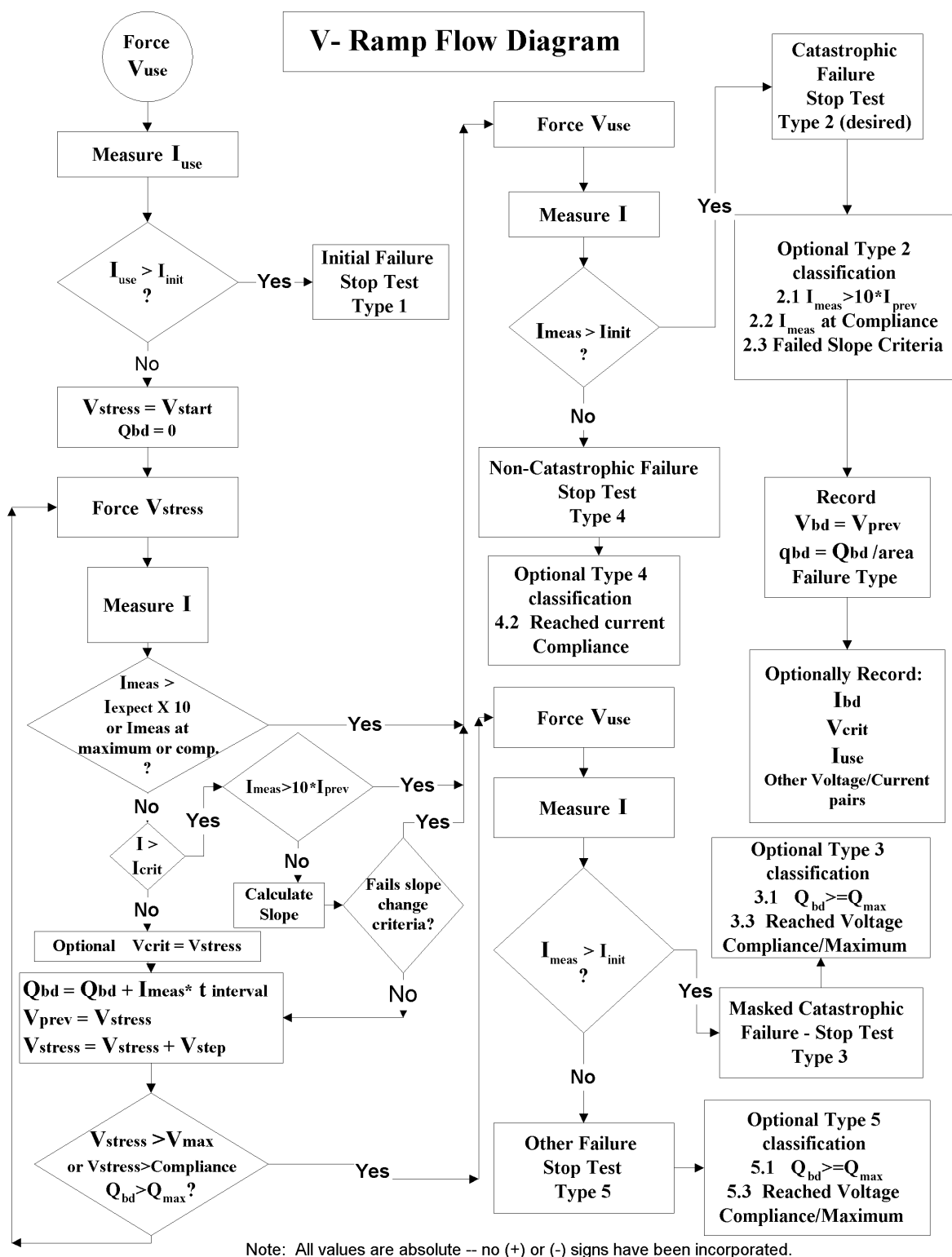


Figure 4.2 — Detailed voltage-ramp flow diagram

4.4 Ramp voltage stress (cont'd)

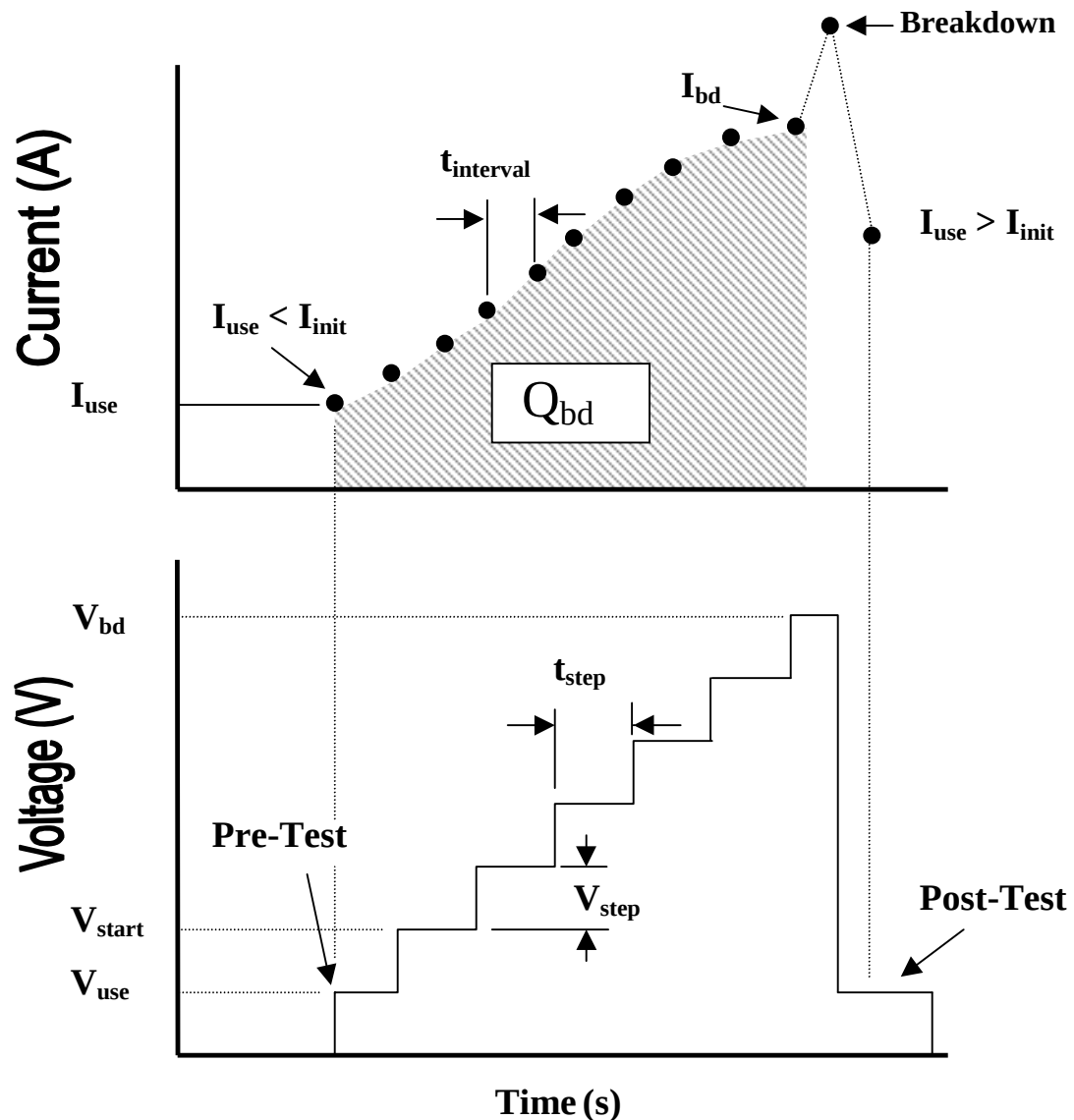


Figure 4.3 — Diagram of typical voltage-ramp test

4.4.1 Oxide breakdown criteria

Oxide breakdown criteria may be specified in several ways. One of the simplest is a measured current that exceeds a specified failure current. Unfortunately, device series resistance can limit oxide current to values below the specified level. It is therefore essential that the oxide failure criteria be carefully specified. Described below are the oxide failure criteria. Oxide failure is defined when one of the following criterion is satisfied.