Measuring Electrical Breakdown of a Dielectric-Filled Trench Used for Electrical Isolation of Semiconductor Devices

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Introduction

Semiconductor devices employ insulating dielectric materials for electrical isolation between active elements and layers that are susceptible to electrical breakdown. The breakdown voltage is the level at which the insulating dielectric begins to allow charge flow. Unlike conducting materials, this charge flow tends to be non-linear. That means that below a threshold voltage no charge will flow, and at or above that voltage a rush of charge will flow. This rush is termed "avalanche breakdown," which is a runaway process resulting in a current spike. Once the charge begins to flow, the dielectric material properties become unpredictable. To properly characterize a given film, breakdown voltages must be repeated over different samples.

Several mechanisms give rise to electron avalanche, one of which is by impact ionization.[1] Impact ionization occurs when either an internal or external field, acting on the dielectric accelerates electrons towards the anode, thereby facilitating collisions with ubiquitous neutrals. The result is the formation of electron-hole pairs. Each electron-hole pair gets polarized by the electric field and accelerated. In doing so, it can ionize more neutrals, even though the holes are generally considered to be relatively immobile. This is a continuous process resulting in a rush of free carriers. Another mechanism is by field-emission breakdown. Field-emission breakdown occurs when critical field strength causes electrons to escape from the valence band to the conduction band.[2] Conduction electrons are mobile charge carriers and diminish the insulating properties of the dielectric.

Breakdown voltage is directly related to the dielectric thickness.[2] Its counterpart, dielectric strength, indicates the relationship between thickness and breakdown voltage, and is expressed as a ratio of voltage to thickness. In thin dielectrics (<3 microns), thermal effects due to local Joule heating can cause thermal breakdown at sufficiently high temperatures. This correlates to electrical conductivity through an exponentially increasing function of the temperature. Other factors that contribute to breakdown include occluded particles, surface and material contamination, and water vapor. Each can influence breakdown; actions must be taken to eliminate their contribution to breakdown voltage measurements. Humidity, for example, reduces the resistance of most dielectrics, thus increasing the return current (the current that opposes a charge build-up).[3] Contamination can contribute to leakage currents and charge mobility across isolation areas. Occluded particles such as alkalis or halides can act to increase the breakdown strength.[2]

The S100 Nanomanipulation System **(Figure 1)** can function as a nano- and microprobe and is an ideal tool for dielectric breakdown voltage measurements. When operated inside a scanning electron microscope (SEM), the vacuum environment minimizes moisture. The SEM also allows the material to be imaged to ascertain damaged areas and perform a failure analysis *in situ*. The S100 can also operate in ambient environments for sub-micron probing. The modular design of the system allows for quick interchangeability between the SEM and the optical microscope. Such versatility makes

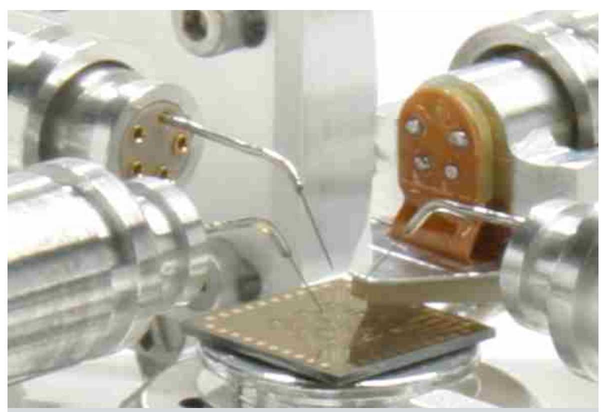

Figure 1 Zyvex S100 Nanomanipulator can function as a nano- and microprobe and is an ideal tool for dielectric breakdown voltage measurement.

the Zyvex S100 the premier system for manipulation and nanometer-scale/micron-scale device probing.

Device Probing

The S100 System is a manipulator designed for nanometer precise resolution. It uses two types of mechanisms for motion: coarse positioners consisting of piezo-motor based, scratch drive actuators allowing linear translation; and fine positioners consisting of piezo tube/piezo stack actuation, which are mounted to the coarse positioners. The positioners are controlled by a joystick/keypad, and move in each of the cardinal directions with a resolution of less than 5 nanometers and a range of 12 millimeters. The piezo-electronically actuated center-sample stage rotates clockwise and counterclockwise with a resolution of 5 microradians. At the end of each fine positioner is a five-pin plug into which probes or other end effectors can be affixed. These probes are affixed into the S100 positioners by a friction fit. One can check connectivity through the system with a multimeter, as all of the probes are electrically accessible via the S100 cabinet. Positioners are used to move the probes into place, and the sample is aligned with the rotational stage.

The S100 may be operated under ambient environments using an optical docking station or in vacuum under an SEM. Each has its advantages, and the required environment is a function of the application. The vacuum environment maintains a low relative humidity, keeping moisture from precipitating electrical breakdown. Using a scanning electron microscope will enable the user to image and probe nanometer-scale devices. However, vacuum environments require more preparation time. For "quick and dirty" measurements, one would opt for an in-air set-up to minimize the amount of time spent on the experiment. In-air testing can be performed quickly with short preparation times with S100, but data acquired from in-air testing is susceptible to further scrutiny if variables such as humidity are not taken into consideration.

One can apply a field and measure current using probe style end-effectors controlled by the S100 System. In either environment, to properly gauge breakdown voltage, one must eliminate alternative paths for current to flow. The current must be a strict measure of the charge flow caused by the applied field across the dielectric. If there are alternative paths for charge to flow between the probes, current will be detected before dielectric breakdown, and the data will not accurately reflect the breakdown voltage.

When contacting the surface, simply touching the contact pads, electrodes, or dielectric surface may not be sufficient to pass current (due to contact resistance). Contact resistance occurs at the boundary between two materials. It can be attributed to many things such as oxidation layers, contamination layers, points of contact, etc. Oxide can grow on metal probes and results in poor ohmic contact. Contamination layers can act as insulation between the metal probe and contact pad. To ensure contact, apply the probes onto the contact area with enough force to make them rub against the surface.

Additionally, ensure that the coarse positioning motors are switched off before taking measurements. The noise from the motor will interfere with the electrical signals.

Considerations for Probing in Air

Zyvex offers a convenient Optical Docking Station option that allows the S100 head unit to be used in-air under an optical microscope. The optical docking station consists of an X, Y-translation stage with an S100 mounting ring, a long working distance optical stereo microscope, a ring light, and an adaptor assembly for the cables. All of these components are mounted neatly onto an optical breadboard for easy adjustment.

Essentially, one can use the S100 operated in-air as a joystick controlled micro-prober station. If possible, operate the S100 in a clean room to eliminate dust, control humidity, and prevent contaminants from building up on the devices. High humidity environments should be avoided due to the influence of excessive water vapor on breakdown voltage. Likewise, low humidity labs should be avoided due to the increased potential for electrostatic discharge through the device.

Considerations for Probing in Vacuum (SEM)

Scanning electron microscopes are typically used to image metal surfaces or metal coated samples. The electron beam impacts the target surface, and scattered electrons are collected by a detector and processed for imaging. The sample must be conducting and must be held at ground potential. This is so that the electrons from the e-beam will either scatter or be dissipated through the SEM. If charging occurs, the electron detectors will be overloaded. Though this may not cause any damage to the detectors, imaging will be impossible. Samples are held to ground by attaching them to metal stubs with double-sided conducting tape or silver paint. The metal stubs are affixed into the SEM with set screws or into the

S100 with conducting tape. The S100 is held to ground potential through the SEM translation stage.

After moving all probes into contact with the device, turn off the electron beam and the motors. Perform all electrical measurements with the electron beam and motors off to reduce noise and charging effects. If repositioning is necessary, repeat the steps above.

Special Devices

Many devices have exposed dielectric layers, such as microelectromechanical systems (MEMS). These devices will need special attention for in-vacuum probing because they are more difficult to isolate electrically. One way to isolate them is by placing them on an insulating surface, like a printed circuit board (PCB).

It may seem that imaging with the SEM would not be possible since the devices have no discharge path. Typically, placing a device on a non-conducting surface will result in the sample charging along with the surface. Upon attempting to image, one would notice the overall brightness increase very quickly over time (see **video** at http://www.zyvex.com/Products/MEBD_001a.htm). This increasing brightness is the sample charging. As the S100 probes come into contact with the device **(Figure 2)**, the brightness will suddenly decrease, indicating that the probe has dissipated the charge build up (keep in mind that higher target voltages result in more charging). Because the S100 can image and perform breakdown voltage measurements on free-standing, electrically isolated devices in an SEM, it is an ideal tool for the application.

Figure 3 shows an example of a four-probe configuration to measure breakdown of an isolation trench separating two actuators of a MEMS gripper. The bright area on the top of the picture shows the PCB material charging. The MEMS device would also be charging similarly if the probes were not making contact to the surface. The isolation trench, seen in the center of the device, is a silicon nitride trench (Si_3N_4) filled with polycrystalline silicon for low cost, structural support **(Figure 4)**.

Ensure that the input/output to each probe in use is either capped or connected to the test station. The technique is not applicable to high-resolution imaging because charge effects will begin to occur and will disrupt the operation of the SEM. The dissipation is attributed to leakage of current through the S100 wiring and cable assemblies. For proper high-resolution

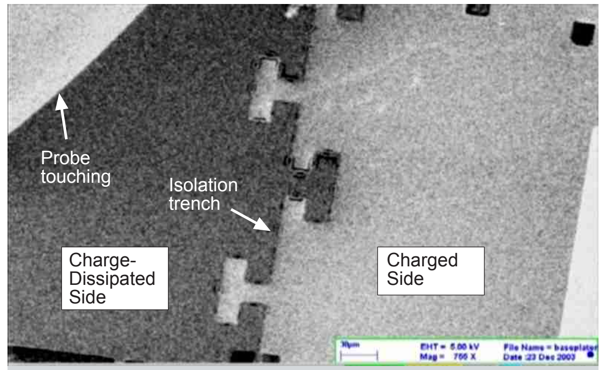

Figure 2 Brightness decreases when probe contacts the isolated device. See www.zyvex.com/Products/MEBD_001a.htm for video capture of this process.

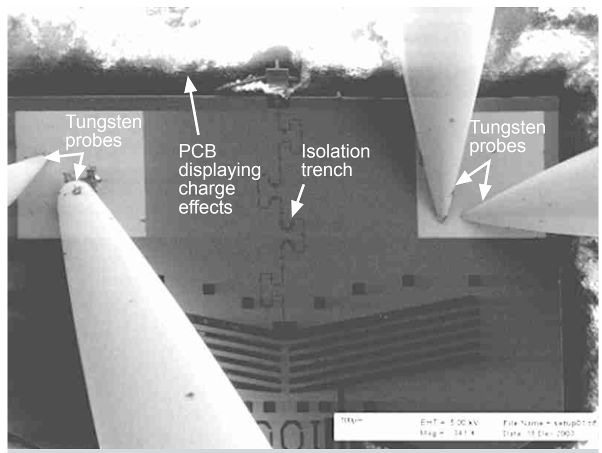

Figure 3 SEM micrograph of the probe configuration for a two four IV measurement. The support structure is a PCB and is charging. The device-under-test is a thermally actuated MEMS device, and is not charging because the probes are acting to dissipate the surface electrons.

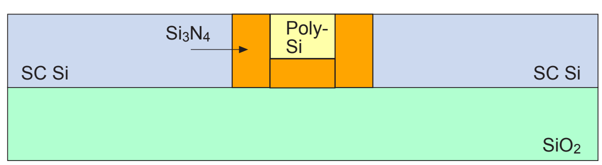

Figure 4 Schematic of the isolation trench from Figures 2 and 3. The silicon nitride forms the insulating barrier. The trench is filled in with polysilicon for low-cost structural reinforcement.

imaging, a true ground plane is required. Also, keep the device-under-test as far from the external pole of the SEM as possible to avoid accidental discharge and damage to the microscope. The video at http://www.zyvex.com/Products/MEBD_001a.htm shows SEM imaging of the isolation trench of a thermally-actuated MEMS gripper. The gripper requires electrical and thermal isolation for the silicon beams to bend to the correct displacement per unit voltage. Here, the isolation trench is being tested for electrical breakdown. The trench is a silicon nitride lined trench that is filled with polycrystalline silicon **(Figure 4)**. Once the probe makes contact to the surface of the device, the charge gets dissipated. This is mainly due to leakage currents through the S100.

Measuring Breakdown Voltage

The best way to characterize a dielectric for electrical breakdown is to perform a voltage sweep across it. Both types of electrical breakdown (impact ionization and field-emission breakdown) are field dependent. That is, there is a critical field strength at which electrons in the dielectric become influenced by the external field. In order to ascertain this critical field strength, one plots current versus voltage as the voltage is swept through a predetermined range.

The range of the voltage sweep depends on the dielectric, and the user must determine this value. Keep in mind that, along with a range, one must consider a sweep rate. Dielectrics are susceptible to local heating effects that cause thermal and electrical breakdown, particularly in thin dielectrics.

The resulting plot should start as an open circuit followed by a sharp current spike at the breakdown voltage (see **Figure 5** for a representative plot). The current will continue to spike until it reaches a threshold which is set either by the protection circuitry or by the hardware. Allowing the hardware to limit the current could result in damage to the S100. It is best to use the test station or some external circuitry to limit the current to 1 mA. The plot displayed here shows a 1 mA protection cut-off enabled with the test station software (Keithley 4200-SCS).

A Word on Safety

Dielectrics are typically designed to withstand a voltage level of two to three times the operating voltage of the device. The S100 can be used with voltage levels up to 500 V and currents up to 1 mA. These current and voltage levels are not arbitrary; they are the maximum values that the S100 can carry without potential damage to the system.

Conclusions

The S100 is the perfect instrument for performing electrical characterization measurements on semiconductor devices. Its versatility is unmatched since it offers the opportunity to measure breakdown voltages in-air and in-vacuum. Working in vacuum helps to minimize the possibility of precipitating a dielectric electrical breakdown by humidity-induced effects. In addition, imaging in an SEM while taking breakdown measurements can allow damaged sites to be ascertained as well as dielectric thicknesses to be measured. Working in air with an optical docking station allows for shorter preparation times and faster experiments. Because the S100 can be moved quickly and easily from vacuum to ambient environments, can provide precision movement for sub-micron device probing, and can accommodate up to 500 V at 1 mA, it is the ideal tool for measuring dielectric breakdown.

References

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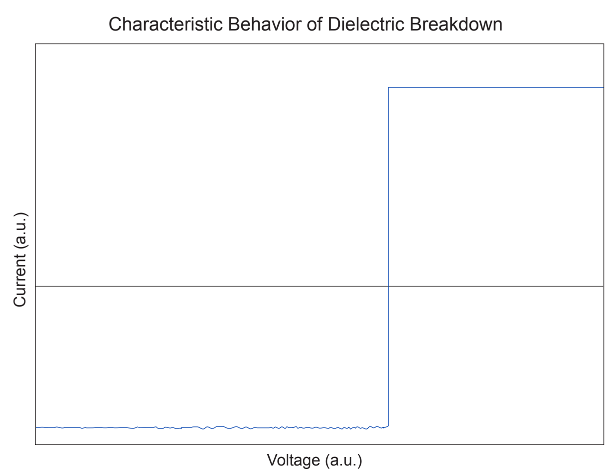

Figure 5 Breakdown of a 50 micron by 2 micron polysilicon-filled nitride isolation trench on a silicon-based MEMS device.