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Current Image Atomic Force Microscopy (CI-AFM) combined with Atomic Force Probing (AFP) for location and characterization of advanced technology node.

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Abstract

Many of the standard techniques of Failure Analysis (FA) are breaking down or becoming less useful as feature sizes drop below 100nm. The tenth micron milestone appears to be a fundamental limitation to many common techniques. Use of Current Image-Atomic Force Microscopy (CI-AFM) combined with Atomic Force Probing (AFP) brings about a combination of technologies, which allow for extension of FA below the nano-scale.

Nano-scale Failure Analysis

Integrated circuit complexity and density have increased to the point that 90nm devices are now in wide scale production and the 65nm process node is under intense development among top tier semiconductor suppliers. Devices and structures below 100nm long are defined as nanoscale.[1] Therefore semiconductor FA is now really nano-scale FA. Nano-scale fault isolation and failure analysis is made extremely difficult, as conventional techniques are not compatible at sub 100nm length scales. Staples of failure analysis such as optical microscopes have become useless when required to image these structures.

Further complicating the analysis is the incredibly thin and leaky gate oxides. Electrical failure analysis (EFA) must take into account even pico-coulombs of beam current when a nano-scale device is subjected to a charged ion beam.[2] It was found that such devices when subjected to far less than 1pC suffered significant device degradation. Another staple of FA community is passive voltage contrast (PVC) carried out with both SEM and FIB tools. This technique suffers from both the charge damage issue as well as a lack of sensitivity to failure modes common to advanced nano-scale processes. As technology scaling progresses, the problems with PVC become critical. The leakier gate oxide requires larger ion beam current to charge the gate in order to show any contrast, also the thinner interlayer dielectric (ILD) for the 65nm node does not leave much room for repeated scans before the area of interest is totally damaged.

One paper from ISTFA found a mere 30% hit rate on fault isolation for PVC.[3] More specifically, because the technique is already suffering from a lack of signal, it is typically only capable of finding shorts and opens. The leaky gate oxides do not give a sufficient signal to noise on good versus bad unless the problem is a gross failure. Resistive contact vias are now beyond the range for PVC to identify.

One of the most useful tools available as a probing technique is the focused ion beam (FIB). The FIB is typically used in construction of micro-probing pads after fault isolation localizes failures to individual transistors of small circuit blocks such as SRAM cells.[4] Floating gate irradiation with a charged beam and charge deposition on interlayer dielectrics ILD can shift device parametrics and shield actual failures lowering confidence in results obtained. Analysis at first level metal (M1) is also often used partially due to the larger separation geometries and also to allow for protection of the inverter gates. Fault isolation at M1 requires some modeling of results and identification of failure mode signatures in order to localize to a particular transistor or via.[5]

SRAM transistor probing in the nano-scale is particularly difficult. FIB deposited pads may be used to contact source, drain, gate, and well/substrate of the transistors. For 90nm and 65nm nodes, the geometry of the pads effectively limits probing to one or two transistors in one cell. As shown in Fig. 1 below, the micro probing pads cover large adjacent areas of the array, completely obscuring nearby cells. Furthermore, sample preparation time may require ~1-2 days if urgent and yield rate for functional samples 50% or less.[6] This technology may not work as transistor technology shrinks below the tenth micron critical dimension.

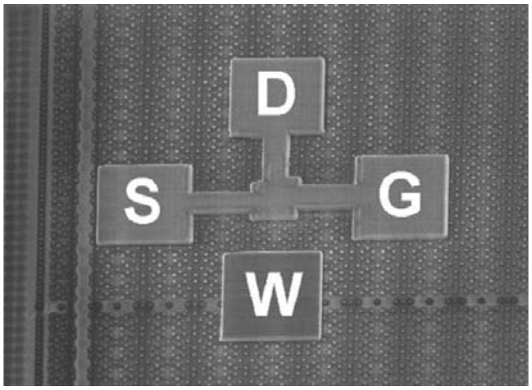

Figure 1. Focused Ion Beam deposited micro pads on 130nm SRAM array.

Atomic Force Microscopy

Atomic Force Microscopy has been used for many years in characterization of electronic materials. The most useful of the techniques for the failure analyst, made possible by the AFM are the electronic measurements such as conductive AFM (C-AFM), scanning capacitance microscopy SCM, and nano-spreading resistance microscopy n-SRM. These measurements are extremely effective in characterizing material properties such as nanoscale doping, conductivity, or resistance.[7 8] For instance SCM[9] and n-SRM[10] have become standard tools for characterizing failures associated with implant profiles, missing implants, and other non-visible defects.[11 12]

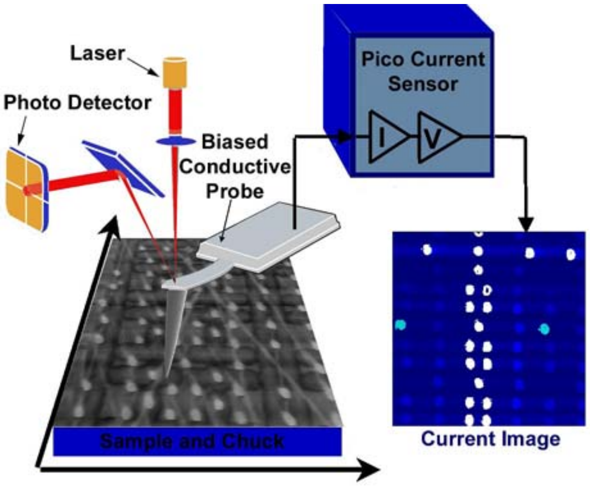

Figure 2. CI-AFM measures the current flow between a biased tip and ground return via the IC sample. The AFM permits force feedback and scanning to allow the probe to ride over the surface mapping the current.

CI-AFM Measurements

Recently, a 90% success rate in identifying root cause failures in samples delayered to contact level has been achieved through the use of CI-AFM.[13] A schematic view of this promising technique is shown in Figure 2. Its application can be considered as being roughly equivalent to Passive Voltage Contrast achieved in the SEM or FIB. However, because the contrast mechanism is current flow, the sensitivity is very greatly enhanced. The higher sensitivity results in a three times higher hit rate compared to PVC. Furthermore, as opposed to PVC, the current data is quantitative in nature. The sample analysis time is minimal and a further capability to take a local sweep and measure the IV spectra for a given contact is critical in determining the electrical characteristic of the failure thus further increases the value of the technique.

In order to generate the CI-AFM images, the author applies 0.5-2 Volts for the sample and the C-AFM sensor measures the current. The IV spectra show diode turn on voltages of 0.7 to 2 Volts. The high bias value is required to overcome the probe and contact resistance inherent in traditional AFM probes.

Figure 3 shows Pico-Current™ images of a 65nm advanced SRAM technology polished to contact level. The probes used for the analysis were made from solid tungsten wire and provide a lower contact resistance and more consistent image quality relative to AFM probes made from coated silicon or diamond. The contact resistance of the wire probes is estimated from the IV results in the following data sets as being a few tens of ohms. The lower contact resistance provides far higher sensitivity and higher current at lower bias. The images are forward and reverse bias images with using positive and negative 10mV applied to the probe. Therefore in the forward bias image on the left current flows out of the probe into the P-type contacts and the reverse contrast on the right. At higher biases, the floating transfer gates become visible and it is possible to distinguish between gate leakages in the pA level.

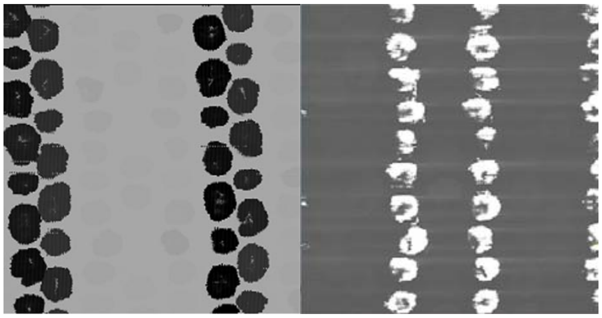

Figure 3. Pico-Current CI-AFM image contrast for a 65nm process technology node. The left image is with the probe forward biased at pos10mV and the right reverse biased at neg10mV.

Results from the advanced technology node using the more conductive probes showed a great deal of contrast in the contacts including several suspected failed sites. One Vss contact is highlighted in Fig 4 below and was found even though no corresponding bit cell failure was registered. An IV sweep of the contact was recorded and compared with a neighboring normal contact and the results are shown in Fig 5. Although the contact does leak in the forward bias condition, it does not affect the operation of the memory cell because it is the Vss contact in this case. However, if the contact leakage was on a different contact in a cell, e.g., one of the contacts to nodes, then the cell would fail. Known failure mode for leaky contacts from physical FA could be due to multiple sources. One example is contact punch through the P/N junction from over etch. Therefore, this technique does demonstrate the capability of detecting contact leakage, which could cause cell failures depending on the location of the contacts in the memory cell.

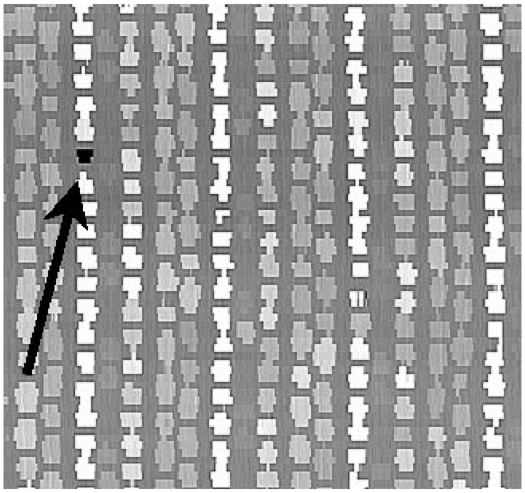

Figure 4 Vss Contact shown by Pico-Current as leaking at the 100pA level.

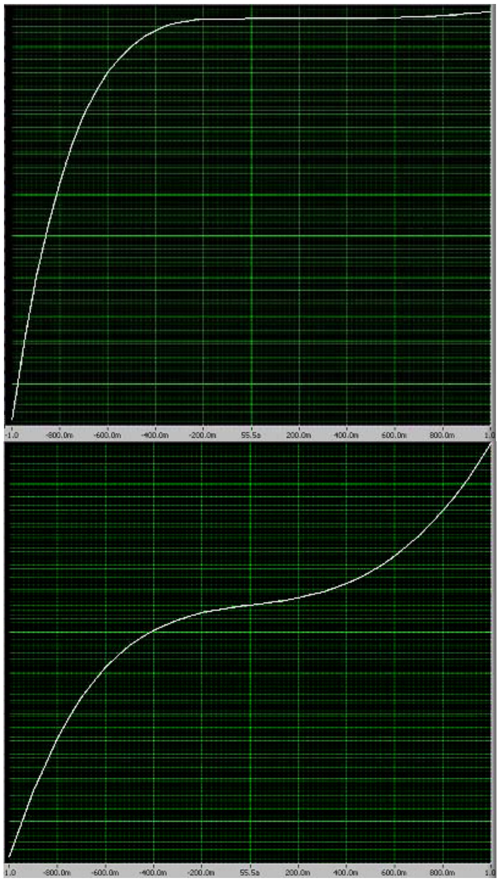

Figure 5. (Upper) IV spectra of a standard Vss Contact in the SRAM cell in figure 4. (Lower) Spectra showing leakage to in forward bias case on the order of 100pA.

Atomic Force Probing at 65nm

The technique of Atomic Force Probing (AFP) is being adopted as a tool to overcome both the single probe limitations in AFM and the limitations to traditional electrical probing under an optical microscope and using FIB deposited micro-pads.[14] [15] The AFP has many inherent advantages relative to other probing methods such as the FIB pads method or in chamber probing in either SEM or FIB or dual beam system. The primary benefit is that the probes being attached to a scanned probe microscope (SPM) with force feedback and piezo actuators. The force feedback permits repeated contacts and scanning (imaging) without bending the probe tip. The primary disadvantage is in alignment of probes onto a given device since the AFP system lacks an overview image of the probes as is available in an in chamber prober.

The AFP has advantages and disadvantages relative to traditional AFM. Though the system has superior positioning accuracy with closed loop scanner positioning in all three axis, the configuration has a higher noise floor than AFM tools designed strictly for imaging. The advantages are that the system uses probe tips made from solid tungsten for excellent contact stability and low resistance however; the size of the probe wire will be generally higher that conventional etched silicon probe tips. Collectively, these features allow the AFP to gain durability and ohmic contact at the expense of imaging resolution.

The trade off is partially offset by the ability to perform CI-AFM imaging in-situ while locating the feature (cell) of interest and aligning the probes. The current images are of excellent resolution and contrast and contain valuable information for fault isolation as discussed above.

The trade-offs between microscopy performance and probing capability is not only mandated by the probe and scanner configurations. The AFP allows multiple probes in very close proximity to permit probing of multiple terminals of nanoscale devices. For the ultra-high density SRAM arrays measured below, 3 of 4 probes must be contacting in >1/50th μm^2!

It is also non-destructive to allow further FA done on the failure sites located. Examples of 65nm transistor ID-Vds & Vgs curves are show in figures 6 and 7. The contact resistance is estimated to be a few tens of ohms and therefore, real device operating parametrics can be extracted from the data. The AFP combined with CI-AFM capability provides a natural progression for nano-scale FA allowing combination of FI and root cause in a single tool platform.

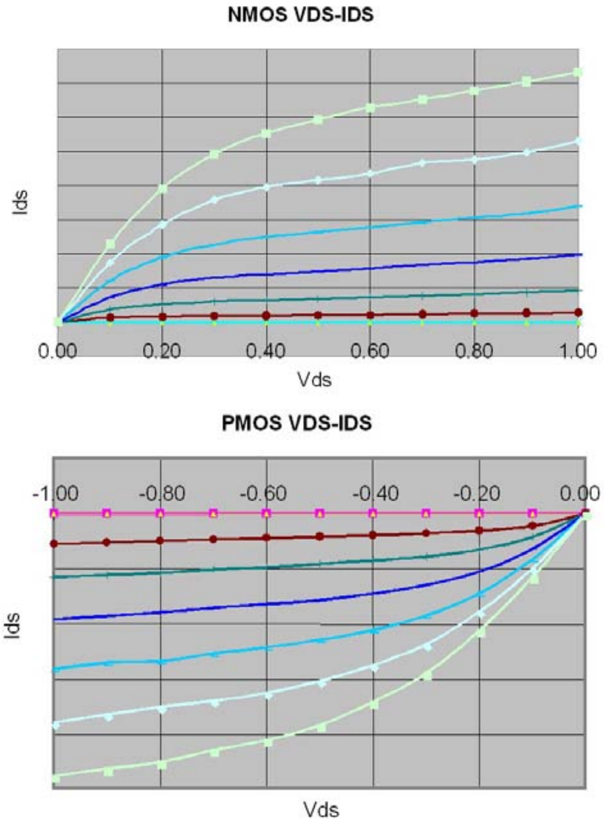

Figure 6. *NMOS and PMOS Ids vs Vds from pull up and pull down gate from SRAM cell used above.*

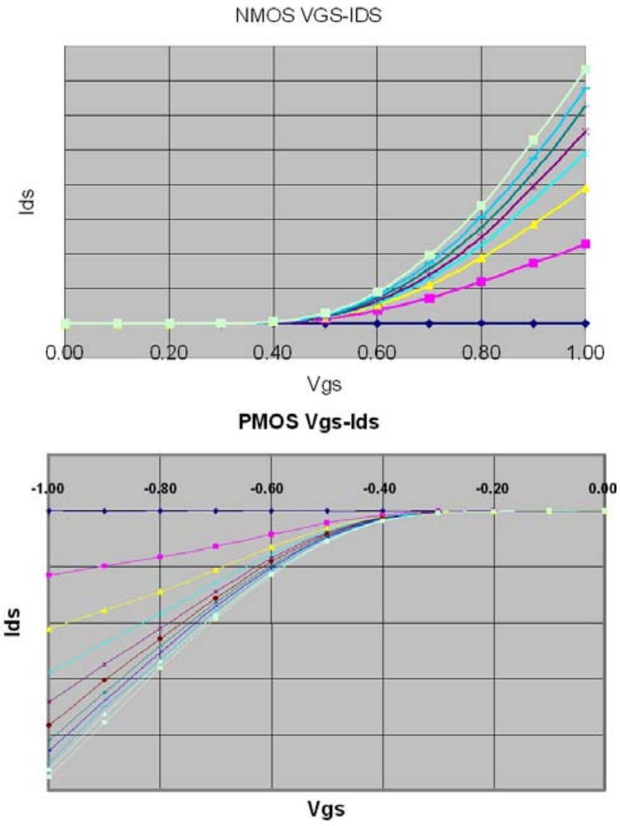

Figure 7. NMOS and PMOS parametric extraction displayed as Ids vs Vgs.

Conclusions

Challenges for nanoscale FA are not currently being met by existing toolsets. Due to sensitivity to both dimension size and charged beam sensitivity, current FI and FA techniques of passive voltage contrast and FIB deposited micro-pad probing are suffering when faced with sub 100nm devices. The clear advantage of the AFP is the ability to carry out all of the functions of CI-AFM and analytical probing on such nanoscale devices. Combining multiple probes to accomplish parametric data extraction as part of the same analysis allows for fault isolation and root cause identification while using the same tool. Adoption of the scanned probe microscope as a probing tool will further increase the importance of this technology.

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