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Scanning Capacitance Microscopy

BY:
ANDY ERICKSON, PETER HARRIS
MULTIPROBE

INTRODUCTION

Since its commercialization Scanning Capacitance Microscopy (SCM) has become the preferred technique for imaging dopant variations in semiconductor devices. SCM is used to measure implant profiles and to develop semiconductor processes. In contrast with PicoCurrent, which is effective in measuring resistivity, the SCM module is more sensitive to dopant and charge in the sample.

HOW SCM WORKS

When the SCM tip is brought into close proximity with the sample surface a Metal/Oxide/Semiconductor (MOS) capacitor is formed between them, where: M is the metal probe, S is the semiconductor material and O is a thin dielectric formed formed on the semiconductor surface. Free carriers within the sample are able to move under the influence of an AC electric field applied by the conductive probe (tip).

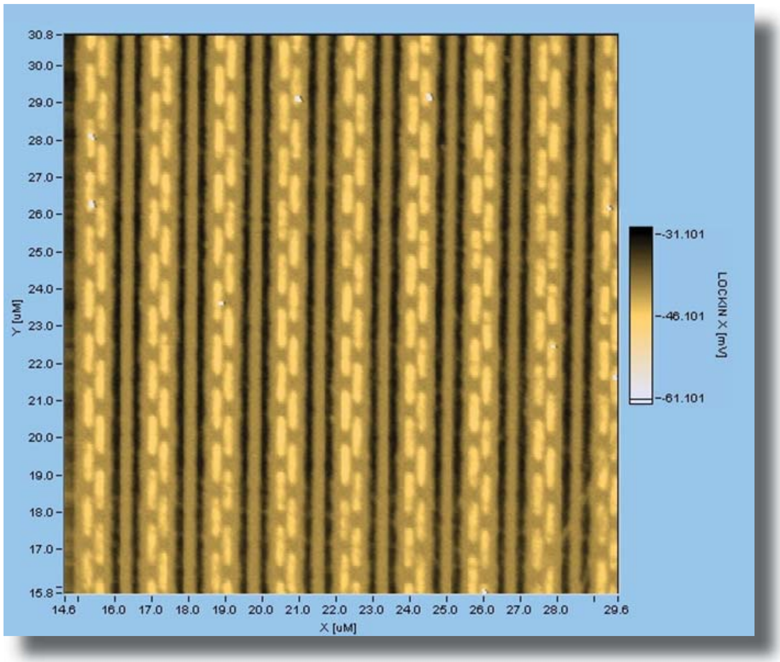

Figure 1. SCM of an SRAM array after the gates have been removed.

The capacitance measured by the SCM sensor varies as the carriers move towards (accumulation) and away from (depletion) the probe. This is shown schematically as figure 2. When the sample is fully depleted the measured capacitance is that of the oxide plus the depletion layer. When carriers are accumulated at the surface, the measured capacitance is that of the oxide layer. This capacitance variation in response to the tip-applied field forms the basis of the SCM measurement.

If we consider the system to be an MOS capacitor then it is helpful to think about the variation in capacitance as being the result of a change in the separation of the plates of a parallel-plate capacitor. While this is a simplified view it is still useful. However, since the interaction is three dimensional parallel plates are only an approximation.

The capacitance between two plates is given by;

$$C = \varepsilon A/t$$

Where:

ε is the dielectric constant
A is the area
t is the spacing between the plates

Therefore capacitance is high when the plates are closest.

Under accumulation the charge is

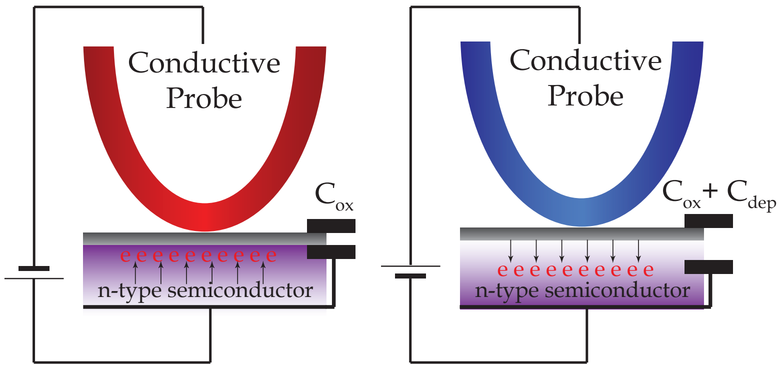

Figure 2. The capacitance measured by the SCM sensor (not shown) varies as the carriers move towards (accumulation) and away from (depletion) the probe.

attracted towards the surface. This is analogous to the bottom plate moving upwards. The plate separation t shrinks and the capacitance increases. For n-type material the measured capacitance is therefore highest when the applied voltage is positive. The capacitance decreases as the bias is shifted negative as a result free carriers being pushed away from the surface, analogous to an increase in the plate separation, figure 3.

Movement of free carriers and hence the amplitude of the capacitance variation is a function of the dopant level of the sample directly beneath the probe. For heavily doped materials the carriers do not move far. Hence, the measured capacitance variation between accumulation and depletion is small. The opposite is true for lightly doped semiconductors which yield a large capacitance change. These variations, and hence the signal measured by the SCM sensor, can be seen in the CV curve for a doped material. Figure 3 (left) shows the CV curve associated with an n-type material at two different dopant levels. The CV curve represents the way the carriers or depletion region moves in response to applied voltage.

If we consider the SCM case as it applies to the CV curve it can be seen that an applied AC bias δV between the tip and sample will produce a corresponding capacitance variation, δC. As noted previously the amplitude of this capacitance variation yields information about the level of dopant directly beneath the tip. Amplitude by its nature however is always positive. There is therefore no way to differentiate the dopant type, n or p, simply by looking at the amplitude of the δC/δV data. To the SCM sensor, when imaging in amplitude only mode, both n- and p-type material appear the same.

If you now consider the CV curve for a p-type semiconductor, figure 3 (right), then you will see that the slope of the CV curve is positive. Hence, if the phase of the δC/δV signal is analyzed there is found to be a 180 degree phase shift between n- and p-type material. By taking both the amplitude and phase components of the δC/δV signal from the SCM sensor it is possible to differentiate not only the dopant level but also the dopant type. When the tip is scanned relative to the sample images are obtained that reveal the dopant variation in two dimensions. When coupled with the correct sample preparation access to three dimensional dopant variation is possible.

WHAT SCM IS USED FOR

The AC bias, δV, applied via the probe relative to the sample, moves carriers resulting in a change in capacitance, δC. The capacitance variation, δC, measured by the sensor is amplified with the aid of a lock-in amplifier. Output from the lock-in amplifier in the form of δC/δV amplitude and/or phase is then displayed as an image. The contrast mechanism for the image is the change in the measured capacitance and hence contained within the image is information on both the dopant level as well as the dopant species.

The sensitivity of the SCM sensor is of the order of attoFarads (10^{-18} F) enabling the possibility of scanning samples at

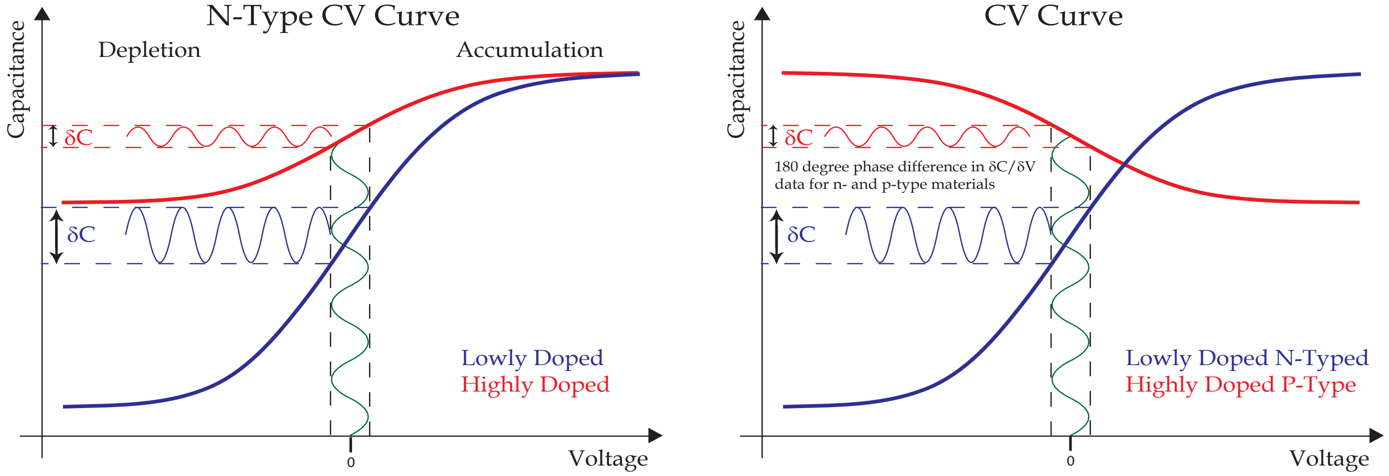

Figure 3. CV curves for a heavily (red) and a lowly (blue) doped n-type semiconductor (left). The amplitude of the SCM data (δC/δV) is larger for lightly doped materials. The CV curve on the right shows δC/δV for both n- and p-type materials. Notice both the change in amplitude as a function of doping concentration and the phase shift with dopant species.

the silicon or contact level. For these two cases the capacitance change measured will vary over several orders of magnitude.

AT THE SILICON LEVEL

Samples may be imaged at the silicon level in one of two geometries. The simplest of these is a top-down scan with samples prepared by de-processing back to the silicon level whilst taking care not to introduce too much topography. Sample preparation is usually accomplished with a combination of mechanical lapping and etch chemistry chosen specifically for the device architecture in question. Upon completion the sample will have topography variations of the order of a few nanometers.

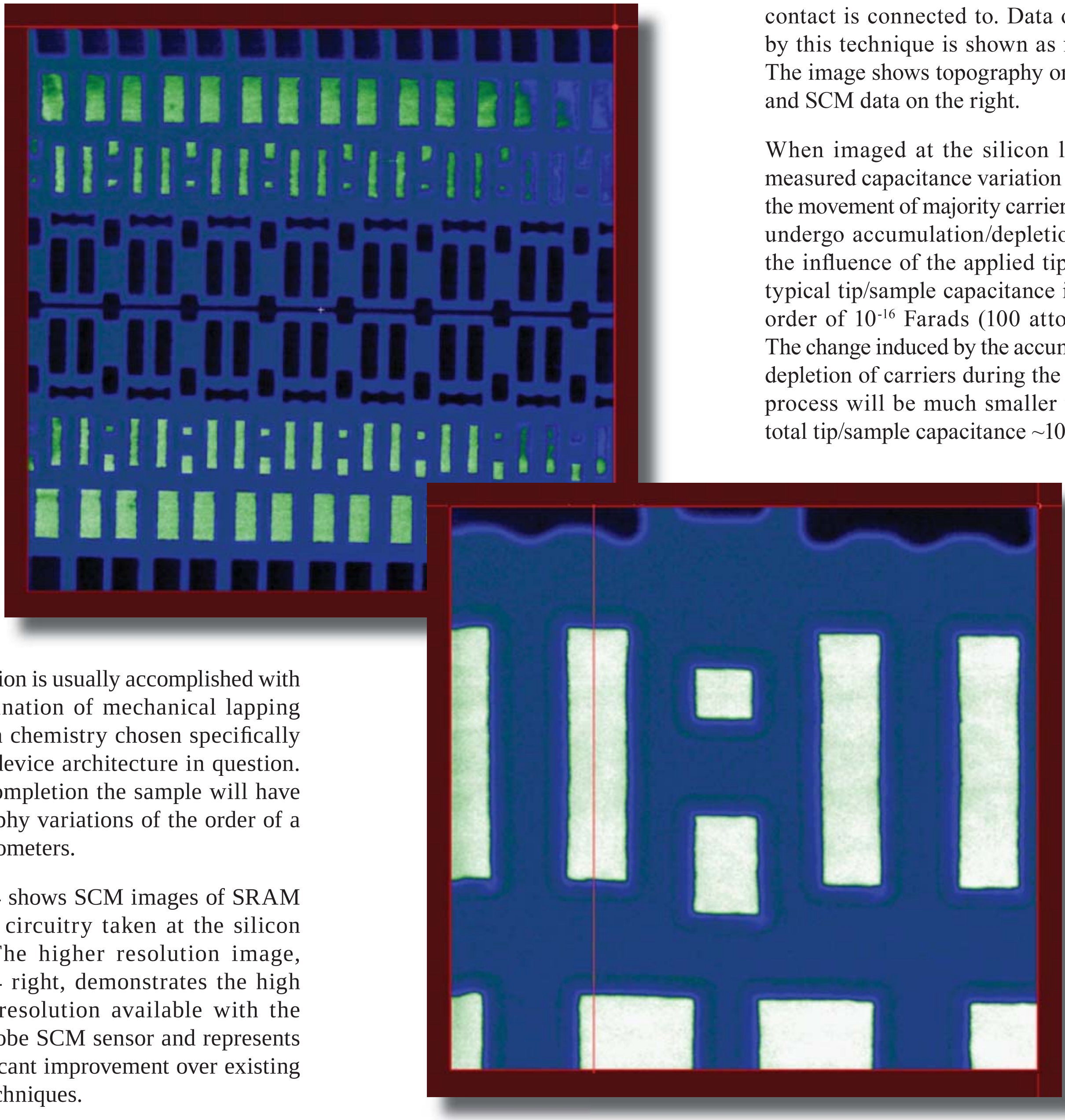

Figure 4. SCM images of SRAM support circuitry. The image on the right is a higher resolution scan of part of the image on the left. The image shows the high spacial resolution of the SCM sensor.

Figure 4 shows SCM images of SRAM support circuitry taken at the silicon level. The higher resolution image, figure 4 right, demonstrates the high spatial resolution available with the MultiProbe SCM sensor and represents a significant improvement over existing SCM techniques.

By cross-sectioning the sample the implant profile as a function of depth is exposed to the SCM probe and sensor. Sample preparation for this kind of analysis represents a significant challenge with today's device technologies especially with the need to hit a single transistor. Sample preparation aside, the cross-sectional analysis of samples at the silicon level provides the user with information that is unattainable with any other method. After years of SCM imaging this orientation has become the most important for device visualization and failure analysis.

AT THE CONTACT LEVEL

At the contact level SCM is used to image the sample in much the same way as current measurements are done. Samples are lapped back to the contact level using standard lapping techniques. A short chemical etch is performed leaving the metal contacts a few nanometers proud of the silicon surface. Imaging a sample at the contact level measures the capacitance variations of what ever structure the contact is connected to. Data obtained by this technique is shown as figure 5. The image shows topography on the left and SCM data on the right.

When imaged at the silicon level the measured capacitance variation is due to the movement of majority carriers as they undergo accumulation/depletion under the influence of the applied tip bias. A typical tip/sample capacitance is on the order of 10^{-16} Farads (100 attoFarads). The change induced by the accumulation/depletion of carriers during the imaging process will be much smaller than the total tip/sample capacitance ~10aF.

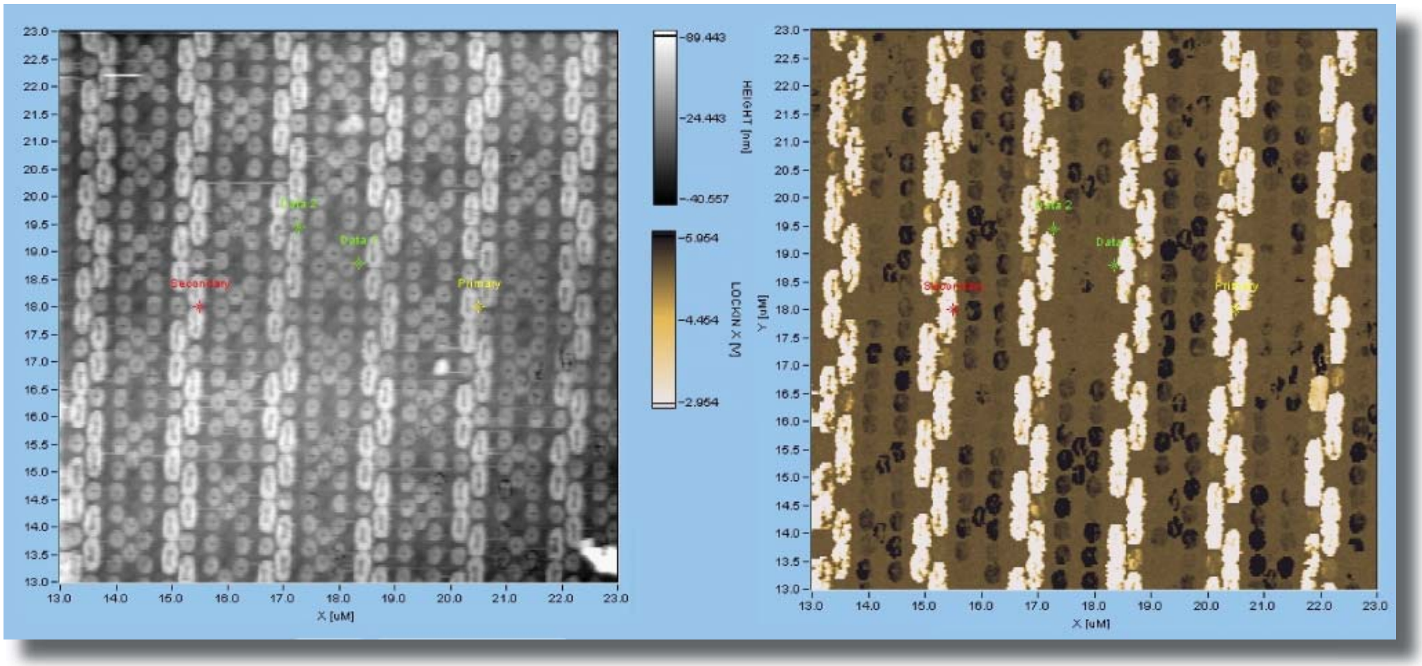

Figure 5 Topography (left) and Scanning Capacitance (right) of an SRAM array at the contact level.

Data obtained in this configuration is primarily used for the visualization of implant regions of a device. This is critical information for the failure analysis process that cannot be obtained with any other technique.

In contrast capacitance variation seen by the SCM sensor at the contact level is no longer determined by the probe/silicon interaction. In this imaging orientation the contrast mechanism is defined by what is connected to the contact in question. Differences between source/drain implant, well connection, and gate poly, etc. are easily measured. These structures have a much higher capacitance associated with them than the tip/silicon capacitance discussed earlier. A gate capacitance for a minimum geometry device for instance is about 300aF The capacitance of a source or drain diffusion is of the order of femptoFarads. For example a typical DRAM trench capacitor has a capacitance of around 30fF.

SCM FROM MULTIPROBE

A Significant disadvantage of existing SCM sensor designs is their inability to allow other measurements at the same time. The sensors themselves are designed to be modular and only used when SCM imaging is required. You cannot for instance make a picocurrent image with the SCM sensor in place. Design limitations of the electronics prohibit this resulting in a huge reduction in productivity. Prior to removal of the sensor the tip must be withdrawn and hence the image or probing location is lost. Each type of measurement; SCM, current or voltage etc., requires that a different sensor be mounted on the imaging platform, and the site of interest relocated.

The SCM sensor from MultiProbe represents the next generation in SCM imaging tools. The electronics are specifically designed to allow SCM, DC, AC and parametric measurements without the need to remove the SCM sensor or probe. This directly translates to an increase in productivity and throughput. With the high SCM spacial resolution MultiProbe SCM represents a significant improvement over existing SCM systems.

MultiProbe
819 Reddick Street
Santa Barbara, CA. 93103
Tel 805.560.0404 Fax 805.560.0414
www.multiprobe.com