Scanning Capacitance Microscopy (SCM) of a Power MOSFET

SCM provides doped region distribution mapping, profiling and dimensional analysis for the research and development, failure analysis and quality control of electronic components.

Introduction

Progress in technology largely depends on the continued miniaturization of electronic components. Smaller components will enable increased switching speeds and device densities for faster computing, larger memory capacity, and improved digital image quality. The current state-of-the-art devices are already below 10nm in size. Characterizing these devices is becoming increasingly challenging because some traditional techniques do not have the required spatial resolution to address such small structures. An alternative method to study these devices is Scanning Capacitance Microscopy (SCM), an AFM-based technique. SCM produces maps of the distribution of electrically active carriers in semiconductors with high lateral resolution. During an SCM measurement, a metallized probe is brought in contact with a semiconductor sample to form a metal-insulator-semiconductor (MIS) capacitor, with the insulator often being the natively grown oxide. An AC bias is applied to the sample, which causes the accumulation and depletion of carriers and the resulting capacitance variations are detected with a GHz resonant capacitance sensor. The probe is raster-scanned across the surface to produce several types of SCM images under normal operation:

(1) The dC/dV amplitude image shows relative dopant levels.

(2) The dC/dV phase image indicates dopant type distribution.

(3) The SCM data image combines the information from the prior two image types.

(4) Along with the electrical information, height data is also collected simultaneously during a SCM measurement.

In this application note, a commercially available power Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) was analyzed using SCM. Power MOSFETs are common power devices used in many applications such as consumer electronics, automotive electronics, power supplies, voltage converters, and battery chargers.[1] While the power MOSFET characterized in this application note was an older technology than the current state of the art, it was selected because it was a commercially available, non-proprietary device. It is possible to resolve much smaller structures than this with SCM on current generation samples.

Experimental

A power MOSFET was de-packaged, cross-sectioned, mechanically polished, and electrically connected to the AFM stage. Optical microscopy and SEM mages of the sample top-down and in cross-section, obtained after sample preparation, are shown in Figures 1 and 2.

SCM images were acquired on a Dimension Icon AFM instrument. In SCM mode, a 15µm × 15µm area was analyzed. The corresponding height image is shown in Figure 3. The topography differences of these images are presented in colors where brown is low and white is high. The z-range is noted on the vertical scale bar on the right side of the image. SCM images were captured concurrently with the topography image (Figures

1 Williams, R.K. et. al, “The Trench Power MOSFET: Part 1 – History, Technology, and Prospects”, IEEE Transactions on Electron Devices, 64, 674, (2017).

3-6). In the dC/dV amplitude image (Figure 5), the brighter colors signify lower dopant concentrations and darker areas have higher dopant concentrations. In the dC/dV phase image (Figure 4), the yellow color corresponds with p-type doped regions and the brown color indicates n-type doped regions. The SCM data image (Figure 6) combines the information in the dC/dV amplitude and dC/dV phase images, with dark purple indicating low p-type doping and bright yellow meaning low n-type doping.

Section analysis of the SCM images was performed to characterize representative doping profiles (Figures 4-6). Line profiles were drawn through the dC/dV phase, dC/dV amplitude and SCM Data, along the lateral distance indicated by the white lines drawn on the SCM images in Figures 4-6.

Results and Discussion

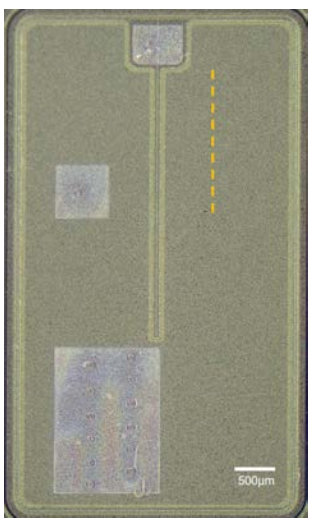

Figure 1: Top-down optical microscopy view of the depackaged die. The dotted orange line shows the plane that was cross-sectioned.

SCM can be performed top-down or in cross-section. Extensive experience in semiconductor device sample preparation, such as de-packaging, cross-sectioning to a specific target region, and expert fine mechanical polishing, is critical for success. In Figure 1, a top-down optical microscopy image of the de-packaged die is shown, where the orange dotted line indicates the cross-section plane. The SEM image of the die after cross-sectioning and polishing showcase the high quality of polish required for successful SCM analyses (Figure 2).

The SCM data was captured at approximately the region shown in the yellow box in Figure 2. In the topography image, the source metallization and polysilicon gate are evident near the top of the region, but no details about the doped structures are visible (Figure 3). The doping distribution is immediately visible in the SCM images, revealing that this is an n type epilayer power MOSFET device (Figures 4 and 6). The n- epi layer can be seen from the dark brown contrast in most middle portions of the dC/dV phase image (Figure 4). Immediately below the metal and polysilicon gate layers, are two p doped well regions with thin n doped source regions on either side. The elongated, vertical extensions are p columns.

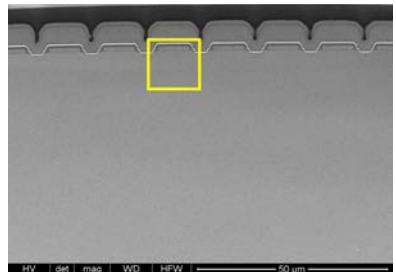

Figure 2: SEM image of the prepared cross-section. The yellow square indicates the analysis area for the 15µm x 15µm SCM images.

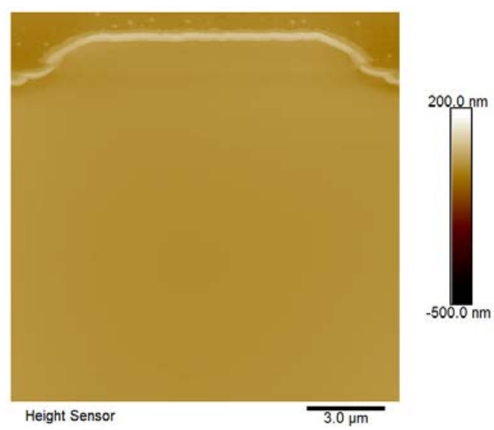

Figure 3: AFM height image of the cross sectioned Power MOSFET (15µm x 15µm x 700nm).

Representative doping profiles, shown in Figure 4-6, can be used to compare relative doping levels and to measure the lateral dimensions of doped regions. dC/dV phase image helps evaluate the doped region dimension. For instance, the dC/dV phase line profile is taken along the white line in Figure 4. Moving from the left to the right direction along the line trace, one can quickly pinpoint that the p-type to n-type transient occurs at 1.7µm, and

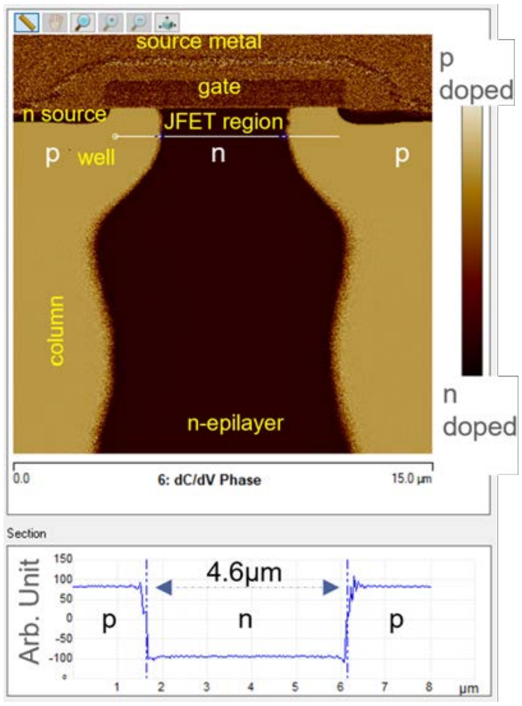

Figure 4: SCM image of the cross sectioned Power MOSFET. Top: dC/dV phase (dopant type) image (15µm x 15µm). Bottom: The blue trace is the dC/dV phase line profile (relative doping type) along the white horizonal line in the phase image on the top.

the next n-to-p transition happens at 6.3µm. The n-type region distance noted as "JFET (junction-gate field-effect transistor) Region" between the two transition locations is 4.6µm.

The dC/dV amplitude image is shown in Figure 5. The amplitude image helps evaluate dopant-level distribution. One may assess the p/n junction's depletion region profile and dimension. From left to right in the amplitude line profile, the p-type amplitude plateau decreases near 1µm to a minimum amplitude value of around 1.7µm. It increases to a n-type amplitude plateaus value at around 2µm. Such curvy "v" amplitude profile variation reflects the p/n junction depletion region profile, which, in this example, occurs over ~1µm distance.

The SCM data image is shown in Figure 6. The SCM data comprises dC/dV phase and dC/dV amplitude images. Such superimposed data facilitates determining different dopant types and levels from one SCM image. Thus, from the SCM data line profile shown in Figure 6, one can determine both locations of the p/n junction transition points and that the form of the dopant level changes around the pn junctions simultaneously.

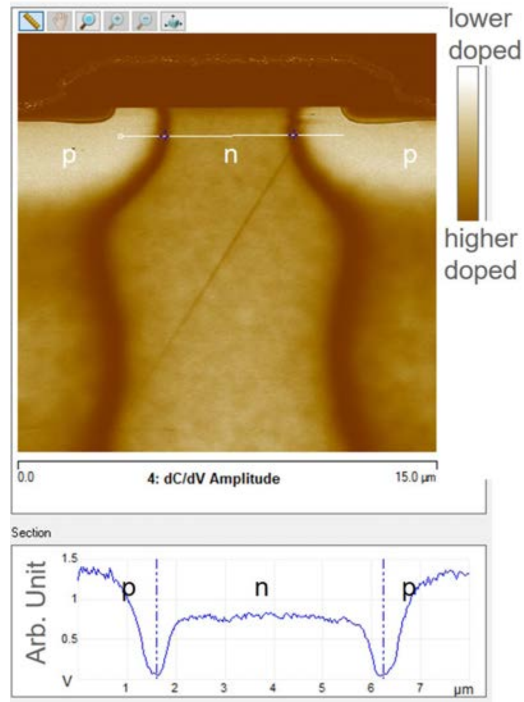

Figure 5: SCM image of the cross sectioned Power MOSFET. Top: dC/dV amplitude (relative doping levels) image (15µm x 15µm). Bottom: The blue trace is the dC/dV amplitude line profile (relative doping levels) taken along the white horizonal line in the amplitude image on the top.

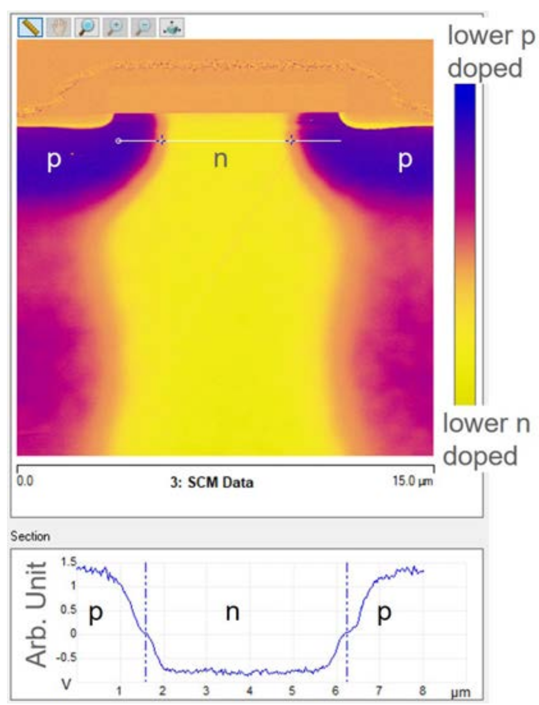

Figure 6: SCM image of the cross sectioned Power MOSFET. Top: SCM data (relative dopant type and doping levels superimposed) image (15µm x 15µm). Bottom: The blue trace is the SCM data line profile (relative dopant type and doping levels) along the white horizonal line in the SCM data image on the top.

Conclusion

As electronic components are further reduced in size, SCM will be an indispensable characterization method for the research and development, failure analysis, quality control, and reverse engineering of these devices. In this application note, a commercially available power MOSFET was analyzed with SCM to illustrate the wealth of information that can be obtained from this technique. Although the selected structures were relatively large, much smaller devices can be investigated with SCM. Additionally, SCM is not limited to silicon-based materials, as shown in this example, but has been successfully used to characterize devices on various compound semiconductor substrates as well. When used in conjunction with other techniques (e.g., SIMS, SEM, TEM, OBIRCH, and emission spectroscopy, SSRM, sMIM, KPFM, PFM), SCM can contribute to a complete picture of complex electronic devices and help explain device performance. Contact us today to learn how we can help with your next project.