Unexpected surface implanted layer in static random access memory devices observed by microwave impedance microscope

W Kundhikanjana 1, Y Yang 1, Q Tanga 2, K Zhang 2, K Lai 1, Y Ma 1, M A Kelly 1, X X Li 2 and Z-X Shen 1

1 Geballe Laboratory for Advanced Materials, Department of Applied Physics, Stanford University, Stanford, CA 94305, USA
2 State Key Lab of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, People’s Republic of China

E-mail: wkundhik@stanford.edu and zxshen@stanford.edu

Received 31 August 2012, in final form 25 November 2012
Published 3 January 2013
Online at stacks.iop.org/SST/28/025010

Abstract
Real-space mapping of doping concentration in semiconductor devices is of great importance for the microelectronics industry. In this work, a scanning microwave impedance microscope (MIM) is employed to resolve the local conductivity distribution of a static random access memory sample. The MIM electronics can also be adjusted to the scanning capacitance microscopy (SCM) mode, allowing both measurements on the same region. Interestingly, while the conventional SCM images match the nominal device structure, the MIM results display certain unexpected features, which originate from a thin layer of the dopant ions penetrating through the protective layers during the heavy implantation steps.

1. Introduction
The ever-shrinking feature size of state-of-the-art semiconductor devices demands local probes with nanoscale resolution for design and characterization purposes. To date, two widely deployed electrical scanning probe techniques are scanning spread resistance microscope (SSRM) [1, 2] and scanning capacitance microscopy (SCM) [1–3], both built on top of the atomic force microscope (AFM) platform. In SSRM, the high-resolution conductivity map is measured through the dc current flow from the probe tip to a remote contact electrode. Such experiments are difficult for samples with native oxides. The results on complex device structures are hard to interpret due to the complicated current path. SCM, on the other hand, overcomes the limitation by using a high-frequency (often at the microwave range) capacitance sensor to obtain the local electrical information. Because of this improvement, SCM has found several applications in characterizing deposited oxides, determining carrier types and concentrations and performing failure analysis [1–3]. However, most commercial SCMs do not directly measure the tip-sample capacitance because of the strong background from unshielded probes, but rather the capacitance change induced by a low-frequency modulation (around 10 kHz) that drives the semiconductor underneath into accumulation or depletion regimes. Such a differential capacitance, or dC/dV, measurement results in non-monotonic response as a function of doping concentration, since low dC/dV signals are expected for both metallic (e.g., heavily doped) and insulating (e.g., dielectrics or depletion) regions. Furthermore, the large ac voltages may modulate a thick layer (up to micrometers) of the underlying carrier densities and complicate the data interpretation. As a result, SCM is still regarded as a qualitative local tool in the semiconductor industry [2].

The recently introduced scanning microwave impedance microscopy (MIM) further eliminates the above problems...
by directly measuring the real (MIM-Re) and imaginary (MIM-Im) components of the tip-sample impedance [4]. The technique is based on a near-field interaction at 1 GHz frequency, in which spatial resolution is determined by the tip apex size, currently about 50 nm. A notable innovation here is our shielded cantilever design, which greatly reduces parasitic tip-sample coupling that leads to topographical artifacts and environmental noise pickup [5]. With this feature, it is now straightforward to detect tiny tip-sample capacitance change—as small as 1 aF [4]. The elimination of low-f modulation ensures the monotonic response in the MIM-Im channel as a function of the local conductivity. Finally, when necessary, the $dC/dV$ experiment is easily performed in MIM for additional information, such as carrier type, of the sample.

In this paper, we demonstrate the MIM experiments on a static random access memory (SRAM) sample. Using two standard staircase samples, we confirm that the MIM-Im response is monotonic as a function of carrier densities, while the $dC/dV$ amplitude peaks at an intermediate doping level. The MIM images on the SRAM devices show features unexpected from the nominal doping maps, which are attributed to a thin layer of dopants that went through protective layers during the ion-implantation processes. We explain why such surface effects are not captured by the $dC/dV$ measurement.

2. Experimental setup and standard samples

The schematic of our MIM setup is shown in figure 1(a). Details of the electronics [4] and our shielded cantilever probes [5] can be found elsewhere. Microwave signal at 1 GHz is sent into a shielded probe and a reflected signal is measured. The low input power of $-14$ dBm was used. As previously discussed in [6], the MIM-Im signal, which is proportional to the tip-sample capacitance, is a monotonic function of the sample conductivity, while the MIM-Re signal, which reflects
the resistive loss, peaks at intermediate doping levels. Only MIM-Im images are reported in the rest of the paper for a clear comparison with the dC/dV data. Note that the latter can be easily achieved by applying an ac modulation (typical $V_{ac} = 0.5$ V at 5 kHz) on the bias-T and demodulating the MIM-Im signal with a lock-in amplifier.

The difference between MIM and dC/dV measurements is illustrated in figure 1 using standard p-type and n-type epi-layer staircase silicon wafers (IMEC, Belgium, part number T8_3 and ST3). The samples are mounted on the side with silver epoxy for good electrical grounding, and the side surfaces are polished before scanning. Figures 1(b) and (f) show MIM images of the p-type (n-type) sample. Each layer is labeled with only the order of magnitude of the doping concentration, with the exact numbers and corresponding conductivities listed in the caption. For comparison, dC/dV images on both samples are shown in figures 1(c) and (g), with typical line cuts plotted in figures 1(d) and (h).

To further emphasize the monotonic response to local conductivity of MIM, we plotted average MIM (dC/dV) signal as a function of local conductivity in figures 1(e) and (i). Simulated MIM signal using finite element analysis is also plotted in figure 1(e) [4]. Both the simulation and the experimental data show that the MIM signal increases monotonically as increasing conductivity and doping concentration. However, deviation from the simulated response is observed at conductivity $\sim 10$ S cm$^{-1}$, which is likely due to carrier redistribution under the influence of the tip. More rigorous calculation is required to fully match the experimental signal. Meanwhile, in figure 1(i), the dC/dV amplitude reaches a maximum around 50 S cm$^{-1}$ ($10^{10}$ cm$^{-3}$) for both carrier types. The non-monotonic dC/dV response is easily understood because neither heavily doped nor nearly intrinsic semiconductors can have appreciable capacitance changes induced by the ac modulation. Monotonic response to the local conductivity is a clear advantage of MIM over the dC/dV measurement. Moreover, a flat-band dc voltage on top of the ac modulation is often needed in conventional SCM, which can be affected by the oxide thickness, the work function of the tip and the carrier type [7, 8]. In the following section, we will also show that, due to the strong modulation of carrier densities underneath the tip, the SCM may miss some surface effects in complicated structures, which are readily captured by our MIM.

3. Results and discussions

Figures 2(a) and (b) show the simultaneously taken AFM and MIM images of a SRAM sample provided by Bruker Corporation, CA. Similar samples have been thoroughly studied by many techniques [9–11] and are currently used as test samples for commercial SCMs (see for example [12]), and thus is a good standard to test the relative merit of MIM. The dielectric layer and polysilicon gate are completely removed, allowing access to the underlying silicon layer. A cartoon of the designed sample structure is sketched in figure 2(c), showing two types of MOSFETs, hereafter labeled as rectangular (NMOS) and H-shaped (PMOS) devices. Table 1 lists the carrier types and doping levels of individual regions [10]. As discussed below, these sample parameters match the dC/dV images taken by both our electronics and commercial SCMs (not shown). The nominal conductivities derived from table 1 also explain most of the MIM results. The n+ and p+ electrodes, with rough surfaces due to the implantation damage, are brightest in figure 2(b) because of the high conductivity. Note that the surface roughness, which affects the tip-sample contact areas in the scanning, does couple into the MIM images. The signal decrease in the narrow lightly doped drain (LDD) and channel regions, both resolved in figure 2(b). In between the p-epi and n-well areas, a low conductivity depletion region is observed as a vertical thick dark line.

Two surprising features, however, are identified in figure 2(b). First, except for the two vertical lines inside the rectangle, bright regions around the source and drain electrodes are seen for the rectangular devices. This is in direct contradiction to the map in figure 2(c), and was not reported by previous studies [9, 10]. The second effect is relatively subtle. According to table 1, the n- and p-channels and the n-well should have similar conductivities, which are higher than that of the p-epi layer. Our data, on the other hand, show systematically lower signals in the channels than in the p-epi or n-well background. We emphasize that the
dark features in the rectangle device and the channels are not
due to a dead layer at the surface because increases in the
conductivity can be observed by imaging with a fixed bias
on the tip ($V_{tip}$). Figure 2(d) shows examples of the MIM images with $V_{tip} = -3$ (left) and $-1$ V (right). The entire p-
epi region becomes brighter as well as the channel regions.
Negative voltage induces charge accumulation at the p-epi
and the n-channels regions for the rectangular devices; thus higher contrast is observed. For the H-shaped device, lower conductivity is observed for the n-well region.

In order to understand these two peculiar features, one
needs to make a clear distinction between the MIM and dC/dV measurements. In conventional SCM experiments, the dc offset and the low-f ac modulation, both in the order of
volts, drive the charge carriers in and out of the semiconductor
underneath the tip. The MIM probe, on the contrary, only
applies millivolts of microwave excitation to the sample
surface. As a result, MIM is more sensitive to a thin surface
layer, while SCM detects the nonlinear effect on a thicker
layer modulated by the bias voltage. It is therefore reasonable
to associate the observed anomalies in MIM with effects very
close to the surface. In addition, the double line features are
sharper compared with other structures and the alignment
with the p-channels, suggesting that the relevant step had to
occur after the gate structure was formed. The only possible
processes are the implantation of the electrodes, which also
involved high-energy implantation.

In figure 3, we illustrate the cross section (a) and the top
view (b) of the sample during the heavy ion-implantation steps
that create the electrodes. The n-type and the p-type implants
were two separate steps, with photoresist protecting the
opposite MOSFETs. During these procedures, the electrodes
were covered with a thin oxide layer; the channels had both
the oxide and poly-silicon gate on the top; and the rest of
the device was protected with thick-field oxide (figure 3(a)).
Ideally, the implanted ions can only go through the thin
oxide and should be blocked by the thick-field oxide and the
poly-gate. In the actual fabrication, however, the field
oxide could be thinner than the desired value, for example
from over-polishing, leading to penetration of a small amount
of high-energy ions through the protective layers. In the
n- or p-channels, these leak-through dopants compensate
the channel carriers, resulting in lower conductivity on the
very surface. For the rectangular device, the same effect
also occurs underneath the field oxide, which is responsible
for the higher conductivity seen in the MIM data. The
double vertical lines inside the rectangle were protected by
both the field oxide and the poly-silicon gate; therefore, the
conductivity here was not altered. Such surface implanted
layers are not seen around the H-shaped devices because of
the shallower profile for the p+ implants. Figure 3(c)
shows simulated doping profile for n+ and p+ implants
(TSUPREM3, Synopsys, Inc.) in SiO2 using parameters from
[10], which were $4 \times 10^{15}$ cm$^{-2}$ As$^+$ at 100 keV for the
n+ regions and $2 \times 10^{15}$ cm$^{-2}$ BF$^+$ at 45 keV for the
p+ regions, and a typical annealing condition of 900 °C and
30 min [13].

As a final remark, the dC/dV amplitude and phase images
taken by the same tip are shown in figures 4(a) and (b),
which are comparable to results from commercial SCMs
[12]. For easy comparison with figure 2(b), the color scale
in figure 4(a) is chosen such that regions with lower signals
appear brighter. It is obvious that the dC/dV response agrees
with the nominal doping level in table 1. The moderately doped
p-epi and n-well regions show higher dC/dV amplitudes than
the depletion region in between them and the heavily doped
n+ and p+ electrodes. The phase image provides additional

| Doping type | Con. (cm$^{-3}$) |
|-------------|-----------------|
| p-epi       | $2 \times 10^{16}$ |
| n-channel   | $2 \times 10^{17}$ |
| n-LDD       | $5 \times 10^{18}$ |
| n$^+$       | $2 \times 10^{20}$ |
| p-epi       | $2 \times 10^{17}$ |
| p-channel   | $1 \times 10^{17}$ |
| p-LDD       | $3 \times 10^{18}$ |
| p$^+$       | $4 \times 10^{19}$ |

Figure 3. (a) Cross section and (b) top views of the device structure
during the ion-implantation process. The thin surface implanted
layers in (a) are sketched by the dotted lines. The n-type (black
arrow) and the p-type (gray arrow) implants are two different steps,
with photoresist covering the other device during the implantation.
(c) Simulated doping profiles for the n+ (thick solid line) and
p+ (thin solid line) implantation processes on SiO2. The dashed
lines indicate the doping levels of the p-epi (gray) and the n-well
(black).

Table 1. Nominal doping concentration of each region and the carrier type.

| Region   | Doping type | Con. (cm$^{-3}$) |
|----------|-------------|-----------------|
| n-well   | p           | $2 \times 10^{17}$ |
| p-channel| n           | $1 \times 10^{17}$ |
| p-LDD    | p           | $3 \times 10^{18}$ |
| p$^+$    | p           | $4 \times 10^{19}$ |
information about the carrier types, with opposite signals between the p-epi and n-well and signals on the electrodes in the middle. We emphasize that the bright areas around the n-electrodes and the double dark lines inside the rectangle are not evident in figure 4. And the n- and p-channels show the same dC/dV responses as the surrounding wells, rather than lower signals in the MIM images. We can then conclude that the thin surface implanted layers cannot be captured by the SCM mode, which detects the capacitance change within a relatively thick layer under the tip. With ever shrinking device dimension, such sensitivity to ultra-thin layers near the surface and its combination with the SCM data, which can be recorded in conjunction with MIM, would add important insights to the understanding of device structures.

4. Conclusions

We have shown the microwave imaging on staircase and SRAM samples in both the linear impedance and dC/dV modes. The additional features observed in the SRAM devices are associated with surface implanted dopants, which have not been reported before by other scanning probes. Although the size of the devices in this work is large compared to today’s state of the art, it is a standard to compare existing techniques. We also stress that there is no fundamental limit for a near-field-based technique such as MIM to reach 10 nm spatial resolution. Moreover, the sensitivity to surface conductivity may prove critical for failure analysis. With both capabilities of measuring the surface impedance by MIM and carrier types by SCM, our technique clearly demonstrates great potential for applications in the semiconductor industry.

Acknowledgments

We would like to thank Dr Craig Nakakura for helping us understand the structure of SRAM devices and Dr Chamin Su from Bruker Corporation, CA, for sharing the n-type staircase and the SRAM samples. This work is supported by Center of Probing the Nanoscale PHY-0425897 and NSF grants DMR-0906027.

References

[1] Kalinin S V and Gruverman A n.d. Scanning Probe Microscopy : Electrical and Electromechanical Phenomena at the Nanoscale vol 1 (Berlin: Springer) chapters 2 and 3
[2] Oliver R A 2008 Advances in AFM for the electrical characterization of semiconductors Rep. Prog. Phys. 71 076501
[3] Tangyunyong P and Nakakura C Y 2003 Product development and yield enhancement through failure analysis of integrated circuits with scanning capacitance microscopy J. Vac. Sci. Technol. A 21 1539–44
[4] Lai K, Kundhikanjana W, Kelly M and Shen Z X 2008 Modeling and characterization of a cantilever-based near-field scanning microwave impedance microscope Rev. Sci. Instrum. 79 063703
[5] Yang Y, Lai K, Tang Q, Kundhikanjana W, Kelly M A, Zhang K, Shen Z and Li X 2012 Batch-fabricated cantilever probes with electrical shielding for nanoscale dielectric and conductivity imaging J. Micromech. Microeng. 22 115040
[6] Kundhikanjana W, Lai K, Kelly M A and Shen Z-X 2011 Cryogenic microwave imaging of metal—insulator transition in doped silicon Rev. Sci. Instrum. 82 033705
[7] Smoliner J, Basnar B, Golka S, Gornik E, Löffler B, Schatzmayr M and Enichlmair H 2001 Mechanism of bias-dependent contrast in scanning-capacitance-microscopy images Appl. Phys. Lett. 79 3182–4
[8] Duhayon N et al 2004 Assessing the performance of two-dimensional dopant profiling techniques J. Vac. Sci. Technol. B 22 385–93
[9] Huber H P et al 2012 Calibrated nanoscale dopant profiling using a scanning microwave microscope J. Appl. Phys. 111 014301
[10] Nelson M W, Schroeder P G, Schlaf R and Parkinson B A 1999 Two-dimensional dopant profiling of an integrated circuit using bias-applied phase-imaging tapping mode atomic force microscopy Electrochem. Solid-State Lett. 2 475–7
[11] Baumgart C, Müller A-D, Müller F and Schmidt H 2011 Kelvin probe force microscopy in the presence of intrinsic local electric fields Phys. Status Solidi a 208 777–89
[12] Bruker Corporation Electrical characterization with scanning probe microscopes http://www.bruker.jp/axs/nano/ims/pdf/AN079.pdf n.d.
[13] Plummer J D, Deal M and Griffin P D 2000 Silicon VLSI Technology: Fundamentals, Practice, and Modeling 1st edn (Englewood Cliffs, NJ: Prentice-Hall)