Experimental investigation of interface states and photovoltaic effects on the scanning capacitance microscopy measurement for p-n junction dopant profiling

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Controlled polishing procedures were used to produce both uniformly doped and p-n junction silicon samples with different interface state densities but identical oxide thicknesses. Using these samples, the effects of interface states on scanning capacitance microscopy (SCM) measurements could be singled out. SCM measurements on the junction samples were performed with and without illumination from the atomic force microscopy laser. Both the interface charges and the illumination were seen to affect the SCM signal near p-n junctions significantly. SCM p-n junction dopant profiling can be achieved by avoiding or correctly modeling these two factors in the experiment and in the simulation. © 2005 American Institute of Physics. [DOI: 10.1063/1.1922077]

The International Technology Roadmap for Semiconductors predicted requirements for two-dimensional (2-D) quantitative dopant profiling are for a 2 nm spatial resolution and 2% accuracy by 2016. Scanning capacitance microscopy (SCM) has the potential to fulfill these requirements. SCM detects the differential capacitance dC/dV of the metal-oxide-semiconductor (MOS) structure formed by the SCM tip, a surface oxide layer, and an underlying semiconductor sample. Since the dC/dV is inversely related to the dopant concentration in the semiconductor, it is possible to extract the dopant concentration from the SCM signals. In recent years, SCM models based on the conventional one-dimensional (1-D) analytic solution of the MOS capacitance-voltage (C-V) characteristics have been used to extract 2-D carrier profiles in unipolar samples. At the same time, scanning capacitance spectroscopy, a variant of SCM, has been used to delineate p-n junctions in silicon transistor cross-sections. More recent developments related to SCM dopant profiling include: the improvement of the spatial resolution by reducing the tip size or using beveled samples; the improved understanding of the impacts of interface charges and atomic force microscopy (AFM) laser on SCM measurements; and the improvement of the data interpretation techniques. However, SCM dopant profiling across p-n junctions has not been fully achieved because the interpretation of SCM signals of p-n junctions still remains a challenge.

It is well known that the SCM C-V curves become “U” shaped when the SCM tip is approaching a junction. This is because, when the tip is close enough to the junction (theoretically speaking, within one diffusion length of the minority carriers), the majority carriers in the opposite side of the junction induced by the tip fringing field are able to travel to the inversion region beneath the tip. As a result, holes and electrons will accumulate alternatively beneath the tip when the sample tip dc bias V_{dc} is swept from the positive to the negative, giving the “U” shaped C-V curves. This is a three-dimensional phenomenon that cannot be explained by the above-mentioned 1-D analytic models. To pursue the SCM dopant profiling of p-n junctions, we recently proposed a different approach through comparison of 2-D numerical simulations and the measured peak dC/dV signal as a function of x (the tip position across the junction) profile. However, there was a discrepancy between the simulation and the experimental peak dC/dV profile in the vicinity of the junction. Our further simulation suggested that this discrepancy may be caused by the interface states; i.e., the interface states with an amphoteric energy distribution may depress the magnitude of the peak dC/dV signal near the p-n junction. More recently, we presented an experimental investigation for this interface states effect. A special sample preparation method was used to make samples with different interface state densities and an identical oxide thickness. That is, diamond and colloidal silica suspensions of different particle sizes were used at the final step of the polish process to create different surface damages on the samples, followed by an identical low-temperature oxidation process. By comparing SCM signals of these samples, the effect of interface states has been singled out. However, until now, all the experimental investigation of the interface states effect have been conducted on unipolar samples. Moreover, it has recently become clear that the stray light from the atomic force microscope (AFM) laser can drastically affect the SCM signal, because it generates local nonequilibrium carriers (the photovoltaic effect). The dC/dV signal in the vicinity of p-n junctions should be more vulnerable to the illumination due to the low concentration of equilibrium free carriers in the vicinity of the junction.
this region. Consequently, the interface states and the photo-
voltaic effects have to be well understood in order to extract
dopant profiles of $p$-$n$ junctions.

In this work, the interface states and photovoltaic effects
on SCM signals near $p$-$n$ junctions are experimentally inves-
tigated. Improvements for the extraction of $p$-$n$ junction dop-
ant profile based on the understanding of these two important
effects are also presented.

For the clarity of this letter, we repeat part of the previ-
ous experiment on the unipolar samples first. Samples 1-1 and
1-2 were polished using 0.02 µm colloidal silica and
0.25 µm diamond suspensions, giving rms surface roughness
of 0.233 and 0.482 nm, respectively. Sample 1-2 is supposed
to have high interface states density because greater surface
roughness contributes more silicon dangling bond defects on
the sample surfaces, resulting in higher interface state densi-
ties after oxidation. These two samples were cut from the
same (100) $p$-type wafer with a uniform dopant concentra-
tion of $1 \times 10^{16}$ cm$^{-3}$. Both samples were cleaned with UV-
generated ozone for 20 min, followed by a 300 °C oxidation
in 5% ozone/95% oxygen for 2 h, giving an oxide thickness
of about 4 nm. Figure 1 shows the $dC/dV$-$V_{tip}$ ($V_{tip}=-V_{dc}$) curve of samples 1-1 and 1-2 measured with
different amplitudes (0.1, 0.5, and 1 V) of the sample/tip ac
bias $V_{ac}$ at a frequency of 20 kHz and with the AFM laser
off. The results show that the peak $dC/dV$ values of these
two samples are nearly the same for all the three $V_{dc}$ values.

At the same time, the full width at half-maximum values of
sample 1-2 are bigger than those of sample 1-1, indicating
that the sample preparation method is able to incorporate
higher interface states density in sample 1-2. These results
lead to a conclusion that the magnitude of the peak $dC/dV$ is independent of interface states.

To investigate the interface states and the photovoltaic
effects on the SCM signals near $p$-$n$ junctions, two $n$/$p$
$junction samples were prepared using the above-mentioned
method (i.e., 0.02 µm colloidal silica for sample 2-1 and
0.5 µm diamond slurry for sample 2-2). The junction in
these two samples is formed by a $n$-type epitaxial layer (uni-
formly doped at 4.6 $\times 10^{15}$ cm$^{-3}$, 12.2 µm thickness) and a
(110) $p$+ silicon substrate (uniformly doped at 2.3 $\times 10^{18}$ cm$^{-3}$). Sample 2-2 has a slightly thicker oxide than
sample 2-1. However, based on the above results for samples
1-1 and 1-2, we believe the peak $dC/dV$ values in the neutral
regions of these two samples would be the same if the oxide
thicknesses of the two samples were identical. Thus, we can
normalize the $dC/dV$ data using the peak $dC/dV$ values in the
$n$-type neutral regions.

We measured the peak $dC/dV$-$x$ data of samples 2-1 and
2-2 with the laser on the SCM tip and in the true dark (laser
off) conditions. When the AFM laser is turned off, the feed-
back loop of the cantilever deflection detection circuit will
continue to adjust the driving voltage of the microscope pi-
ezoelectric scanner in the vertical direction attempting to
maintain a constant laser reflection. This may shift the tip
position between when the laser is on and when the laser is
switched off. To ensure the accuracy of the tip position de-
tection, we set the “deflection setpoint” in the feedback con-
trols equal to zero in experiment and performed the measure-
ment of the $dC/dV$-$V_{dc}$ curve with a loop of three steps: i.e.,
with the laser on, the laser off, and the laser on again. Only if
the $dC/dV$ characteristics obtained with the laser-on and
the laser-on-again were identical with each other were the
data accepted and the tip shifted to the next point to continue
the measurement. Using this approach, the $dC/dV$-$V_{dc}$
curves were obtained as the tip scanned across the junctions
in spatial intervals of 0.05 µm. The peak $dC/dV$ values were
then obtained from each $dC/dV$-$V_{dc}$ curve to produce the
peak $dC/dV$-$x$ profile. Note that, the $C$-$V$ curve of neutral
regions takes a shape like a conventional high-frequency $C$
$V$ curve, giving one peak $dC/dV$ value (positive value for
$n$-type and negative for $p$-type region) and when the tip rests
in the depletion region near the junction, the “U” shaped $C$
$V$ curve gives two peak $dC/dV$ values (one positive and one
negative). Thus, the positive and the negative peak $dC/dV$
$-x$ curves overlap in the measured depletion region.

Figure 2 shows the normalized peak $dC/dV$-$x$ results of
sample 2-1 obtained with the laser on (solid circles) and off
(solid line); and the normalized peak $dC/dV$-$x$ data of sample
2-2 with the laser off (solid triangles). A comparison of the two curves of sample 2-1 in Fig. 2 reveals
two effects of the illumination. Firstly, the measured deple-
tion region (or the peak $dC/dV$ overlapping region) is broad-
ened by the illumination. Secondly, there are increases in
magnitude (humps) in the peak $dC/dV$ signal on both sides of
the depletion region in the data measured in the dark as
compared to the data obtained with the laser on. Both of
these two effects can be attributed to the laser generated
excess nonequilibrium carriers. That is, when the laser is on,
the quantity and the recombination lifetime of free carriers
will increase. As a result, the carriers are able to cover a
longer distance across the junction, making the measured
depletion region wider. On the other hand, under the true dark condition, the concentration of free carriers in the depletion region of the p-n junction is lower compared to that in the neutral regions, resulting in bigger values of the peak $dC/dV$ signal. Note that in Fig. 2, as well as in the following Fig. 3, the central positions of the overlapping regions are used as the position reference to align all the $dC/dV$-$x$ curves along the $x$ axis.

Comparison of the two peak $dC/dV$-$x$ curves (laser off) of samples 2-1 and 2-2 in Fig. 2 reveals the effect of interface states. Two differences between these two curves can be observed. The first is that the measured depletion region of sample 2-2, which is supposed to have the higher interface states density, is narrower than that of sample 2-1. This can be attributed to the decrease of the minority lifetime and the carrier mobility at the silicon surface with the increase of the interface defects. The other difference is that there are no apparent humps in the peak $dC/dV$-$x$ curve of sample 2-2 as compared to that of sample 2-1. This validates our earlier simulation results, which show the interface states depress the peak $dC/dV$ values near p-n junctions.

Interface states and the photovoltaic effect both deteriorate the detection of the SCM signal, especially near p-n junctions. Thus, for the p-n junction dopant profiling, experimental data acquired with the true dark condition using samples of low interface charge density are necessary. Figure 3 shows a result of dopant profile extraction of a junction using this approach. The junction is a $n$-type epitaxial layer (uniformly doped at $8.07 \times 10^{16} \text{ cm}^{-3}$, 11.1 $\mu$m thickness) on a (110) $p^+$ silicon substrate (uniformly doped at $2.3 \times 10^{18} \text{ cm}^{-3}$). This sample (sample 3) is used here because, compared to sample 2-1, the experimental peak $dC/dV$ profile of this sample covers full region of the junction with the same measuring distance ($2 \mu$m) due to the narrower depletion region (or the higher dopant concentration). The sample surface was polished using 0.02 $\mu$m colloidal silica to decrease the surface roughness. A new model improved from our earlier model was used for this simulation. This is because the earlier model gave a narrower simulated overlapping region (solid squares in Fig. 3) compared to the experimental peak $dC/dV$ profile (solid line), which can be attributed to that the fringing field around the tip in the earlier model is too small compared to what in practice. In our model, a round tip shape (radius=0.2 $\mu$m) and a higher dielectric constant ($\varepsilon=8$) in the region of air are specified to increase the fringing field around the tip. This new model has no allowance for interface states at this stage. Figure 3 shows that the simulation result of the new model (solid circles) and the experimental peak $dC/dV$ profile, corresponding to the same dopant profile (solid triangles), qualitatively match with each other. This result, plus our earlier simulation work of the SCM interface states model, leads to a conclusion that the SCM dopant profiling of a p-n junction is achievable after taking into account the interface states and the photovoltaic effects in the experiment and in the simulation. The details of this simulation work will be published elsewhere.

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