Comprehensive 2D-carrier profiling of low-doping region by high-sensitivity scanning spreading resistance microscopy (SSRM) for power device applications


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Superjunction (SJ) MOSFETs with low on-resistance and high sustain voltage are widely used as main switching power devices. For the p/n-pillars of SJ-power devices, precise doping at low-doping region below $10^{16}$ cm$^{-3}$ concentrations is required, and thus high-sensitivity 2D-carrier profiling of the pillars is indispensable where conventional SCM is insufficient. Previously, we developed the high-vacuum SSRM enabling high-spatial resolution and site-specific 2D-carrier profiling.

In this study, we investigated comprehensively the feasibility of applying SSRM to SJ-power devices at low doping below $10^{16}$ cm$^{-3}$, with both SJ-diodes and low-doping references. The bias dependence of SSRM was analyzed on SJ-diodes and was compared with T-CAD simulations, and both the p- and the n-pillars demonstrate Schottky-like behavior between the probe and the sample. Consequently, the pn-junction delineation also moved with applied bias. We also performed SSRM on reference-staircase structures with low-doping layers down to $10^{14}$ cm$^{-3}$ of p, n and p/n types, and comparison with SIMS and SRP confirmed the high sensitivity of SSRM. The Schottky contact of the probe-sample was found to be pronounced at low-doping region, particularly p-type doped region. Therefore, the bias polarity should be taken into account to obtain correct information at the low-doping region.

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1. Introduction

High-voltage power devices are required to offer high voltage tolerance, which makes low-concentration doping necessary. To achieve high-performance power devices, exact control of low-level doping is necessary, leading to demands for high-sensitivity 2D-profiling techniques [1,2].

In spite of the urgent requirement associates with power device development, highly sensitive dopant measurements with high spatial resolution remain challenging by conventional 2D analysis methods. Scanning capacitance microscopy (SCM) has been widely used in 2D carrier measurements but the sensitivity is limited to $10^{18}$ cm$^{-3}$, which is insufficient for high-voltage power devices. SCM also suffers problems of contrast reversal that make data explanation complex. In addition, SCM’s spatial resolution is limited to around 10 nm [3].

Scanning spreading resistance microscopy (SSRM) performed in a high vacuum is a promising candidate for 2D carrier mapping with high spatial resolution of approximately 1 nm as shown in Fig. 1, because probe environment reduces the contact resistance between the probe and sample surfaces by eliminating water and contamination layers [4-6]. The spatial resolution was determined by the precision of pn junction delineation by confirmation with T-CAD simulation [6]. The contrast of Fig. 1(a)(b) corresponds to the value of current, which is nearly proportional to net carrier concentration. The bright region has high current and then low resistance and otherwise the opposite. The pn junction and depletion layers near the junction are observed to be resistive. The carrier concentration distribution and pn junction delineation from Fig. 1(a)(b) agree well with T-CAD simulation as shown in Fig. 1(c), and details are shown elsewhere [4-6]. Furthermore, we recently developed a site-specific SSRM (SS-SSRM) method based on a new sample-preparation method using a focused ion beam (FIB) pick-up technique [7-9], which enabled analysis of real bits in 65 nm-node static random access memory (SRAM) devices [8].

For power device analysis, however, high sensitivity is important in addition to spatial resolution to detect low doping concentrations. SSRM has been reported to be effective for real device failure analysis [10,11]. We previously reported the application of SSRM to superjunction (SJ) diode failure analysis [10]. SJ-diode is a typical high-voltage power device, consisting of adjacent p pillars and n pillars that are both lowly doped in the region of $10^{15}-10^{16}$ cm$^{-3}$. Since the balance of the p-pillar and n-pillar doping concentration impacts device performance, precise control is required. By observing the deviation of carrier concentration on p-pillar bottom from the ideal doping profile, we found the root
cause of the lowering of sustain voltage of the SJ-diode, which agrees
well with T-CAD simulation results [10]. It was demonstrated that
SSRM has potential for profiling low-doping level of power devices.
On the other hand, as low doping concentration corresponds to high
spreading resistance, the probe-sample contact resistance also increases
accordingly, making SSRM measurement difficult in this region. The non-ohmic
rectifying characteristics of the probe-sample contact have been reported [12,13], and thus the influence on the measured
pn-junction delineation becomes non-negligible at the low doping
level. The non-ohmic contact needs to be taken into consideration
when measuring 2D profiling in this region to extract real carrier distribution. Because power devices mainly utilize doping region around
$10^{15} - 10^{16}$ cm$^{-3}$, measurement sensitivity under $10^{15}$ cm$^{-3}$ is necessary and should be investigated. In addition, the measured pn-junction delineation dependence on experimental parameters also needs to be clarified.

In this study, we investigated bias dependence of SSRM measurements of SJ-diodes by emphasizing issues from the point of view
of characterization of power devices. We also performed SSRM on reference staircase structures with low-doping layers down to $10^{14}$ cm$^{-3}$ of p, n and p/n types, and comparison with other analytical techniques such as SIMS and SRP, confirmed high sensitivity of SSRM in this region. In addition, we investigated pn junction delineation, and discuss issues concerning SSRM in this low-doping region.

2. Experimental

The 1st sample set was 600 V-class SJ-diode device [10]. The 2nd sample set was p-type doping staircase of $10^{14} - 10^{15}$ cm$^{-3}$ on an n-type substrate. The 3rd sample was a p-type doping staircase of $10^{14} - 10^{17}$ cm$^{-3}$ on a p-type substrate of $10^{16}$ cm$^{-3}$. The 4th sample was an n-type doping staircase of $10^{14} - 10^{17}$ cm$^{-3}$ on an n-type substrate of $10^{15}$ cm$^{-3}$. Cross-sectional specimens for SSRM measurement were prepared by mechanical polishing. A schematic of SSRM measurement for SJ-diode power device is shown in Fig. 2. SSRM measurements were performed in a high vacuum using commercially available diamond-coated Si probes. Experimental details were reported elsewhere [4–9].

3. Results and discussion

3.1. Bias dependence of a failed SJ-diode and comparison with T-CAD simulations

We performed SSRM measurement on the cross-section of a failed SJ-device A with insufficient voltage, and obtained the current image shown in Fig. 3(a) with a zoomed image of the bottom region on the left. The conductance profile along AA' of the p-pillar is shown in Fig. 3(b), indicating that the carrier profile falls 80% in the bottom part of approximately 10 μm in the p-pillar. It was considered that the deviation of dopant concentration at the p-pillar bottom accounted for the lowering of sustain voltage of device A. On the other hand, a SCM image is shown in Fig. 3(c), where we couldn’t figure out significant change at the pillar bottom of signals corresponding to the drops of carrier concentration due to insufficient sensitivity of SCM at the low-doping region below $10^{16}$ cm$^{-3}$. In Fig. 3(d), T-CAD simulation based on degraded profile from SSRM results explains well the voltage lowering of device A from the ideal device, demonstrating the high sensitivity of carrier profiling of SSRM method. The uneven carrier concentration

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along the p-pillar vertical direction was due to the difficulty of process control at this very low doping region. Improved sustain voltage was achieved by increasing the doping concentration at the p-pillar bottom. It is demonstrated that SSRM has sufficient sensitivity to be used for SJ-diode power device doping control.

Although we succeeded in carrier profiling in the vertical direction along the pillar with optimized parameters, the pn-junction delineation by SSRM measurement remains difficult in this doping region. Fig. 4 shows a T-CAD simulation of the lateral profile between p- and n-pillar, demonstrating that compared with dopant profiles, carrier profiles have a broader region corresponding to a broader width of pn junction.

In addition, we also encountered difficulty in this very low-doping region due to the non-ohmic and rectifying contact between the probe and the sample to be measured. Schottky-like behavior was observed as shown in Fig. 5(a), indicating bias and bias polarity dependence of SSRM current image. The sample bias was applied from the left in the sequence of 2 V, 1.5 V, and −2 V. As a result, both the p-pillar and the n-pillar show strong dependence of bias polarity, but whereas p-pillars appear to be conductive at the positive bias condition, the n-pillars are the opposite. A current profile along BB′ is shown in Fig. 5(b), demonstrating the same tendency, in particular, an n-pillar shows an abrupt conductance jump when bias was changed from 1.5 V to −2 V. We choose positive bias for p-pillar and negative bias for n-pillar, assuming the forward direction of Schottky junctions for each doping type between the probe and the sample. Consequently, the exact delineation of pn junction between the p- and the n-pillar also shifts with applied bias.

From Fig. 5, it is concluded that for SSRM measurement on SJ-diodes at this low-doping region must take the Schottky behavior into consideration to obtain correct doping profile information.
3.2. Sensitivity and bias dependence investigation of reference low-doping structures in the region of $10^{14}$ to $10^{17}$ cm$^{-3}$

To investigate the sensitivity of SSRM and to delineate pn junction, we firstly made p-type staircase doping layers on an n-type substrate. The SIMS and SRP results of carrier concentration are shown in Fig. 6(a), indicating different pn-junction position between the SRP and SIMS results, where the SRP shows shallower pn junction than that of SIMS. An SSRM image is shown in Fig. 6(b) with varying biases from the top in a sequence of 1 V, 1.5 V, 2 V, −2 V, and 1.5 V. The dark regions are of low current and high resistance, corresponding to low net carrier concentration. The SSRM images demonstrate bias and bias polarity dependence. It was found that the p-type conductance profiles show similar depth profile with SRP at the positive biased conditions, whereas the n-type conductance profiles are similar to SRP at the negative biased conditions, which are results similar to those presented in Fig. 6. However, the reversely biased conductance profile shows different behavior between the p-type and the n-type samples that the result of the n-type with reversed bias deviated completely in all the doping regions but the p-type has a meaningful data down to $10^{10}$ cm$^{-3}$. This difference indicates that the p-type has more pronounced Schottky behavior than that of the n-type, resulting in a stronger bias polarity dependence. In addition, the Schottky characteristics of between the probe and the p-type region were also observed in the positive bias conditions shown in Fig. 7(b), where the conductance profile biased at 0.5 V differs from those biased at 0.8 V and 1 V.

It is suggested that when measuring the low-doped p-type region such as the p-pillar in SJ-diode by SSRM, an optimized positive bias should be applied to obtain meaningful results reflecting the real doping concentration. This result can also explain the SSRM data of the SJ-diode in Fig. 5.

![Fig. 7. Boron staircase on p-type substrate: (a) SRP, (b) current image, (c) conductance profiles of +1, +0.8, +0.5, −1 V, and −2 V.](image)

![Fig. 8. Phosphor staircase on n-type substrate: (a) SRP, (b) current image, (c) conductance profiles of −1, −0.8, −0.5, −0.3, −0.1, +1, +0.8 V, and +0.5 V.](image)
4. Conclusion

Comprehensive 2D carrier profiling of low-doping region from $10^{14}$ to $10^{17}$ cm$^{-3}$ was performed by SSRM on SJ-diode device and reference staircase $p$- and $n$-type structures. High sensitivity was confirmed and the Schottky contact between the probe and the sample was found to be pronounced at the low-doping region, particularly in $p$-type doped region. The observed $pn$-junction delineations move with applied bias, and the bias polarity should be taken into account to obtain correct information from SSRM measurement at the low-doping region.

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