Simultaneous interface defect density and differential capacitance imaging by time-resolved scanning nonlinear dielectric microscopy

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Abstract
We investigate non-uniformity at SiO$_2$/SiC interfaces by time-resolved scanning nonlinear dielectric microscopy, which permits the simultaneous nanoscale imaging of interface defect density ($D_i$) and differential capacitance ($dC/dV$) at insulator-semiconductor interfaces. Here we perform the cross correlation analysis of the images with spatially non-uniform clustering distributions reported previously. We show that $D_i$ images are not correlated with the simultaneous $dC/dV$ images significantly but with the difference image between the two $dC/dV$ images taken with different voltage sweep directions. The results indicate that the $dC/dV$ images visualize the non-uniformity of the total interface charge density and the difference images reflect that of $D_i$ at a particular energy range.

Introduction
Among the wide band gap semiconductors, SiC has already been in practical use for modern power electronics devices. However, the existing SiC metal-oxide-semiconductor field effect transistors (MOSFETs) still suffer from low channel mobility and threshold voltage instability. In this context, reducing high interface defect density ($D_i$) at SiO$_2$/SiC interfaces has been under ongoing study to reap benefits from the superior material properties of SiC as well as eliminating bulk defects [1]. Tachiki et al. have recently established a novel procedure for the formation of the SiO$_2$ layer and achieved drastic reduction of $D_i$ [2]. As a result, achievable channel mobility has been improved twofold but still one order magnitude lower than expected [3]. $D_i$ trap states drive a change in capacitance of a MOS device and thus affect MOS device performance and reliability.

In order to give the microscopic insights on these problems, scanning nonlinear dielectric microscopy (SNDM) [4-6] has recently been applied for the investigation of the SiO$_2$/SiC interfaces [7-11]. SNDM is a microwave based scanning probe microscopy method with remarkably high sensitivity to the variation in the tip-sample capacitance. SNDM can image the voltage derivative of local capacitance ($dC/dV$) below the conductive tip. It has been found that $dC/dV$ images show non-uniform clustering distributions on various SiO$_2$/SiC interfaces. Interestingly, the degree of the non-uniformity evaluated by the relative standard deviation (RSD) is strongly correlated with $D_i$ levels measured by macroscopic techniques. Therefore, if we understand the physical origin of the correlation between the $dC/dV$ non-uniformity and the interface quality, the $dC/dV$ imaging may be utilized for the quick interface evaluation of SiO$_2$/SiC wafers [7].

In general, $dC/dV$, or the slope of a local capacitance-voltage (CV) profile, can be contributed from the different causes such as fixed charges and dopant concentration as well as $D_i$. For better understanding the relationship between the $dC/dV$ images and interface quality, here we investigate the cross-correlation between $dC/dV$ and $D_i$ images. Nanoscale $D_i$ imaging has recently become possible by local deep level transient spectroscopy (local DLTS) based on SNDM [8, 9]. Here, we use time-resolved SNDM (tr-SNDM) for the simultaneous local DLTS and $dC/dV$ imaging. Unlike the previous setup for the similar experiment [12], tr-SNDM readily permits the correlation analysis of these different imaging modes taken at the exactly same positions on a sample. We show that simultaneous $dC/dV$ and $D_i$ images have similar non-uniform clustering distributions but are not correlated significantly. In addition, we find that the $D_i$ images are correlated with difference images between $dC/dV$ images taken with different voltage sweep directions.

Method
SNDM measures the variations in the tip-sample capacitance using a capacitance sensor typically made of a gigahertz range LC free-running oscillator. The LC oscillator runs on its gigahertz resonance frequency varying with the tip-sample capacitance and thereby permits converting the capacitance variation to the oscillation frequency shift [13]. Conventionally, SNDM has taken a frequency domain approach utilizing a traditional analog setup [4]. A sinusoidal voltage is applied to the sample to modulate the tip-sample capacitance typically at tens of kilohertz (much less than the gigahertz resonance frequency), and the resulting periodic frequency shift is demodulated with such as a frequency demodulator and lock-in amplifier. In this setup, only one particular frequency component corresponding to the modulation frequency is extracted and physical information included in the sensor signal are largely omitted. Therefore, an improved setup called super-higher-order SNDM has been proposed to obtain rich information by utilizing multiple higher harmonic components and actually permitted various extended measurement techniques [8]. However,
because of limited frequency bandwidth and complicated frequency characteristics of the analog setup, these frequency domain approaches basically suffer from narrow measurement bandwidth and signal distortion. The cumbersome calibration is also needed to eliminate artifacts.

On the other hand, a time domain approach, or tr-SNDM, has recently become possible based on modern digital facilities such as a high-speed digitizer and subsequent digital signal processing [9]. Figure 1 shows schematic diagram of tr-SNDM. The raw output of the sensor is directly digitized normally after the down-conversion from gigahertz to tens of megahertz frequency and then the shift of its center frequency is demodulated through band-pass filtering, Hilbert transformation, differentiation, and low-pass filtering. Because of the direct digitization of the raw or down-converted sensor signal, tr-SNDM can perform wider bandwidth measurement and therefore realize distortion- and calibration-free measurement unlike the conventional frequency domain approaches. As a result, tr-SNDM can fully record the accurate capacitance response to an arbitrary voltage pattern applied at each measurement point. This gives flexibility to SNDM measurements, because different voltage patterns can be included in a series. This kind of time division multiplexing measurement will help the correlation analysis of different images taken at the exactly same position.

In our experiment, we apply a rectangular pulse for local DLTS and subsequently small triangular pulse for local dC/dV imaging, as illustrated in Fig. 2(a). These pulse are triggered point-by-point. The first rectangular pulse for local DLTS is applied to observe the capture and emission process of dominant carriers at an insulator-semiconductor interface. Since the dominant carriers are accumulated at the interface while the pulse is applied, the capacitance response is also basically rectangular. However, because of the carriers trapped at the interface defects, small exponential decay can be observed immediately after the pulse is released. By analyzing the exponential decays point-by-point, a $D_{it}$ image can be reconstructed [14]. The subsequent small triangular pulse is employed to obtain dC/dV images. The dC/dV images can be reconstructed from the full wave falling or rising part of the triangular capacitance response by simply dividing the amplitude of the capacitance variation by that of the applied voltage. The images for the falling and rising parts are here called backward and forward dC/dV images, respectively. It is noted that dC/dV corresponds to the slope of a local high frequency CV profile taken with a high voltage sweep rate (tens kilohertz frequency) rather than a quasi-static (dc) voltage sweep used in the macroscopic CV profiling. Our local CV profiling reflects deep depletion. The difference between the backward and forward dC/dV images is defined as a $\Delta dC/dV$. 

**Figure 1.** A schematic diagram of tr-SNDM [9]. Adapted with permission from Fig. 1(a), Appl. Phys. Lett. 111, 163103 (2017). Copyright 2017, American Institute of Physics.

**Figure 2.** (a) One cycle of the applied voltage pulses for the simultaneous local DLTS and dC/dV measurements by tr-SNDM. (b) A typical capacitance response on the as-oxidized SiO$_2$/SiC sample.
image. These $D_{it}$, $dC/dV$, and $\Delta dC/dV$ images are obtained at precisely the same position by tr-SNDM.

As discussed below, the spatial fluctuations on forward and backward $dC/dV$ images can be contributed from those of the total interface charge density including fixed and trapped charges. In contrast, $\Delta dC/dV$ only reflects the spatial fluctuations in a smaller range of interface trap energies determined by the sweep rate of the triangular pulse.

### Results and discussion

The samples were two different n-type 4H-SiC(0001) wafers with $10^{16}$ cm$^{-3}$ dopant concentration and 10 nm-thick thermal oxide layers. One of the sample was only as-oxidized but the other was further treated by post-oxidation annealing (POA) in NO gas for 60 min. at 1250 deg. C to reduce $D_{it}$. We used a Pt-Ir coated conductive cantilever with 150 nm radius tip (NanoWorld, SD-R150-T3L450BPt). The measurements were performed in air at room temperature. The LC oscillator ran at 1 GHz, which was converted to 30 MHz. The sampling rate of the digitizer was 1 GHz. We applied repetitive 1000 cycles of 1 GHz, which was converted to 30 MHz. The sampling rate of the digitizer was 1 GHz. We applied repetitive 1000 cycles of 10 μs-long duration time for local DLTS applied voltage pattern consisted of 0 to -5 V negative measurement point to increase the signal-to-noise ratio. The voltage pulses and averaged the responses at each measurement point to increase the signal-to-noise ratio. The applied voltage pattern consisted of 0 to -5 V negative rectangular pulse with $5 \mu$s-long duration time for local DLTS and subsequent 1 Vpk and 1.5 cycle triangular pulse with a period of 10 μs for $dC/dV$ imaging. As shown in Fig. 2(b), we could see an exponential decay of capacitance after the rectangular accumulation pulse for local DLTS. The exponential decay was analyzed by Fourier DLTS [15] to estimate local $D_{it}$. Here the energy depth of $D_{it}$ under local DLTS analysis was 0.35 eV from the band edge of the conduction band. The capacitance response to the subsequent triangular pulse could also be observed and used for $dC/dV$ and $\Delta dC/dV$ imaging. As mentioned below, $\Delta dC/dV$ imaging is sensitive to $D_{it}$ in a particular energy range determined by the voltage sweep rate and here considered to be comparable with $D_{it}$ imaging by local DLTS.

Figure 3 shows simultaneous $D_{it}$ [Fig. 3(a)], backward $dC/dV$ [Fig. 3(b)], forward $dC/dV$ [Fig. 3(c)], and $\Delta dC/dV$ [Fig. 3(d)] images of the as-oxidized sample. The images including the others below were treated by Gwyddion software [16]. The unit of the $D_{it}$ image is cm$^{-2}$eV$^{-1}$, as in the conventional DLTS analysis. For $dC/dV$ and $\Delta dC/dV$ images, arbitrary units are used because these images here show the raw frequency shifts of the sensor without converting them to the capacitance variations. As previously reported [4, 5, 6], the $D_{it}$, forward, and backward $dC/dV$ images showed the clustered non-uniformity. The spatial average of $D_{it}$ was as high as $4.2 \times 10^{13}$ cm$^{-2}$eV$^{-1}$. These images showed similar clustered non-uniformity. However, as shown in Table 1, the cross-correlation coefficients of the $D_{it}$ with forward and backward $dC/dV$ images were negligible, which indicates that the spatial fluctuations in the $D_{it}$ and $dC/dV$ images were uncorrelated. Figure 4 shows the data for the POA treated sample with the average of $D_{it}$ as low as $1.3 \times 10^{12}$ cm$^{-2}$eV$^{-1}$. The cross-correlations of $D_{it}$ images with forward and backward $dC/dV$ images were also almost zero, as the same with the as-oxidized sample.

Since, for both samples, the $dC/dV$ images were almost uncorrelated with the corresponding $D_{it}$ images, basically, the $dC/dV$ images were slightly contributed from $D_{it}$ at -0.35 eV from the conduction band edge. This is because $dC/dV$ can depend on the whole energy spectrum of $D_{it}$ rather than $D_{it}$ at a particular energy depth. Depending on the time-scale of the applied voltage pattern, $D_{it}$ at different energy levels can contribute to $dC/dV$ in different ways. If the time-scale of the triangular voltage sweep is sufficiently faster than its emission rate, trapped charges filling sufficiently deep levels can act as fixed charges, because the trapped charges cannot emit from
visualizing spatial correlations, we here suppressed the noise by correlated parts, as shown in Figs. 5(e) and 6(e), by multiplying Figs. 5 and 6, respectively. In addition, we enhanced highly applying a Gaussian filter to them in Figs. 3 and 4, as shown in C between the forward and backward dC/dV measurement. Then, the total density of the trapped charges at the deep levels and fixed charges contributes to the fluctuations of dC/dV through the shift of local CV profiles. As for shallower levels, their fast capture and emission of the relevant carriers suppress the capacitance change, or dC/dV, by shielding the penetration of the external electric fields into the depletion layer. Since filling and emptying these levels respectively with backward and forward voltage sweep suppress the changes in the depletion layer capacitance, they make local CV profiles stretched out along the voltage axis and their spatial fluctuations also contribute non-uniformity in dC/dV images. Therefore, unless Dk at different energy levels and fixed charges are spatially correlated, we do not find correlation between dC/dV images and Dk. In other words, the observed uncorrelation in our experiment implies that Dk at different energy levels and fixed charges have no significant spatial correlation among them.

On the other hand, we found that, as shown in Table 1, significantly higher cross-correlation coefficients about 0.3 were obtained between the Dk images and their counterpart ΔdC/dV images. Here ΔdC/dV images are the difference images between the forward and backward dC/dV images. For visualizing spatial correlations, we here suppressed the noise by applying a Gaussian filter to them in Figs. 3 and 4, as shown in Figs. 5 and 6, respectively. In addition, we enhanced highly correlated parts, as shown in Figs. 5(e) and 6(e), by multiplying the normalized Dk and ΔdC/dV images in each figure. Because of the normalization through the division by standard deviation after mean subtraction, the highly correlated parts are positively enhanced while uncorrelated areas take negative values. As shown in Table 1, even for the filtered images, the correlation coefficients are comparable with each of those for the raw images. We consider that the correlation coefficients increase by taking the difference between forward and backward dC/dV images. This is because the contributions to these two dC/dV images from Dk with emission rates comparable with the measurement time-scale are extracted by taking the difference. In fact, the emission rate of Dk here observed by local DLTS (~10 μs) (See, Fig. 2(b)) was comparable with the half a period of the applied triangular pulse (5 μs) for the dC/dV measurement. The time-delayed capacitance response caused by the emission process from Dk at -0.35 eV partly contributes to the generation of a small hysteresis, or minor loop, between backward and forward local CV profiles. In contrast, the contributions from Dk at sufficiently deep and shallow levels that respectively have much lower and higher emission rates than the time-scale of the dC/dV measurement are cancelled out as well as those from the fixed charges, Dk at the sufficiently deep levels is not reflected to ΔdC/dV images because of their much slower emission process than the applied voltage sweep. The trapped carriers at the deep levels do not respond to the voltage sweep. The shallow levels are also not reflected, because they have much faster emission rates and can follow the applied voltage sweep.

ΔdC/dV images thus can reflect Dk at the particular energy range, which is determined by the frequency of the applied voltage pulses. In fact, as already observed in the Dk images, the ΔdC/dV image in Fig. 6(d) for the POA treated sample has a much smaller mean value than Fig. 5(d) for the as-oxidized sample, suggesting the significant reduction of Dk again. We also find ΔdC/dV spatial patterns correlating with those in their counterpart Dk images. As suggested by higher correlation coefficients in Table 1, both samples have similar clustered non-uniformity in the ΔdC/dV images. The difference is that high Dk clusters in Figs. 6(d) and 6(e) are likely to be more concentrated in smaller areas than those scattered entirely in

<table>
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<tr>
<th>Sample</th>
<th>As-oxidized</th>
<th>POA treated</th>
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<tbody>
<tr>
<td></td>
<td>Raw Filtered</td>
<td>Raw Filtered</td>
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<tr>
<td>Backward dC/dV</td>
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<td>Forward dC/dV</td>
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<tr>
<td>ΔdC/dV</td>
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<td>+0.31</td>
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Figs. 5(d) and 5(e). This might suggest that the impacts of the POA treatment are spatially non-uniform even though it significantly reduces $D_n$ macroscopically, while the mechanism has not been understood yet.

Conclusions

We performed the cross correlation analysis of $D_n$, $dC/dV$, and $\Delta dC/dV$ images observed at the exactly same positions using tr-SNDM based novel simultaneous local DLTS and $dC/dV$ measurements. Our results indicate $dC/dV$ images visualize the spatial non-uniformity of the total interface charge density and $\Delta dC/dV$ images reflect that of $D_n$ at a particular energy range. Our finding here suggests that $D_n$ and its energy spectrum might be investigated by taking the difference of $dC/dV$ images taken with different voltage sweep rates.

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