New Generation of Corona-charge Noncontact C-V (CnCV) Metrology for Characterization of Wide Bandgap Interfaces and Deep Interface Traps

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Abstract

We report a new generation of corona noncontact C-V metrology, CnCV, that takes advantage of two unique photo-assisted techniques. The first technique provides a direct determination of the flatband voltage, V_{FB} and the flatband capacitance, C_{FB}. This resolves problems with limited applicability of previous V_{FB} methods and forms a basis for a unique self-consistent multi-parameter characterization of wide bandgap interfaces. The second technique addresses the measurement of very deep interfacial traps that are invisible in conventional C-V. This approach is based on trap photoionization uniquely combined with corona charge bias for control of trap occupation. Monitored with surface voltage, surface barrier and capacitance characteristics, this approach is used to quantify interface traps with a very deep energy location. Examples of the new capabilities of CnCV are presented for oxidized SiC and GaN.

INTRODUCTION

The charge-based corona-Kelvin technique is a non-contact electrical characterization method used by the majority of silicon IC fab-lines [1]. Only recently this technique has been adopted for the needs of wide bandgap technologies, including SiC and AlGaN/GaN [2]. First applications were focused on non-contact dopant measurements and dopant depth profiling creating an alternative to mercury probe CV (Hg-CV) [3]. Excellent precision and repeatability, matching Hg-CV has been demonstrated for epitaxial SiC, GaN and also for HEMT structures and 2DEG profiling [2]. Further non-contact C-V wide bandgap expansion included surface and interface characterization, measurement of the interfacial trap energy spectra, and characterization of complex interfacial instability phenomena including corona-stress induced charging of near interfacial oxide traps (NIOTs). In response to broadening interest, commercial equipment has been introduced by Semilab SDI, namely, the FAaST 210 SiC tool in 2014 and the most advanced CnCV (corona non-contact CV) tool in 2018 [4]. The newest generation of CnCV, with two major refinements, was used in the present study. The refinements are based on novel photo-assisted characterization of interfaces between wide bandgap semiconductors and dielectric films.

The corona metrology uses charging increments, ΔQ_C, and noncontact measurement of the surface voltage, V, with a Kelvin probe. The charge and voltage increments give the non-contact capacitance $C = \Delta Q_C/\Delta V$. In a corona charge bias sweep, the semiconductor space charge, Q_{SC}, and the surface barrier, V_{SB}, are cycled between accumulation and depletion. The method gives a full set of parameters (V, Q, C, V_{SB}) and corresponding characteristics such as V-Q, C-Q and C-V. These characteristics form a basis for quantification of the semiconductor, interface and dielectric parameters.

EXPERIMENTAL RESULTS AND DISCUSSION

In the CnCV tool, high precision corona charging is realized with a constant surface potential charging method originally designed for high precision SiC dopant determination. Principles and experimental details are available in ref. [2]. All measurements presently reported were performed using oxidized n-type SiC and n-type GaN. Therefore, the corona charging sequence involved positive charging to accumulation followed by a negative charging sweep through flatband into depletion. The magnitude of charge biasing was limited to oxide fields below 0.5MV/cm. This limitation was intentionally introduced in order to avoid tunneling effects and charging of near interfacial oxide traps (NIOTs) that are beyond the scope of this work.

The present work focuses on characterization of interfacial traps that are filled in weak accumulation. The negative corona sweep shifts the interfacial traps upwards above the Fermi energy. Shallow traps depopulate via electron emission and are monitored using standard corona non-contact metrology in weak depletion. Occupation of deep electron traps remains unchanged, making them invisible in conventional C-V.

For quantification of interface parameters, the value of actual flatband voltage, V_{FB} is very important. A novel method directly determines V_{FB} using a string of photo-induced surface voltage pulses generated by low intensity UV LED excitation of excess carriers [5].

The flatband condition serves as an anchor point enabling determination of the oxide voltage, V_{ox}, and the surface barrier, V_{SB}, at any given charge, Q_C, as shown in Fig. 1. The corresponding capacitance components are then separated as illustrated in Fig. 2. In deep depletion this allows a determination of the semiconductor dopant

concentration, N_D, needed to calculate Q_{SC} (this is based on V_{SB} and the depletion capacitance). The interface trapped charge is then obtained directly from the charge neutrality condition: $\Delta Q_{it} = -\Delta Q_C - \Delta Q_{SC}$. The interface trap density is $D_{it}=\Delta Q_{it}/\Delta qV_{SB}$. Long time constants limit such D_{it} measurements to about 0.9eV from the band edges. The presence of deeper states has been reported for SiC and GaN interfaces based on photo-assisted C-V and current measurements. In the present work, we adopt the surface photovoltage spectroscopy method invented at MIT 5 decades ago based upon monochromatic sub-bandgap energy illumination [6,7].

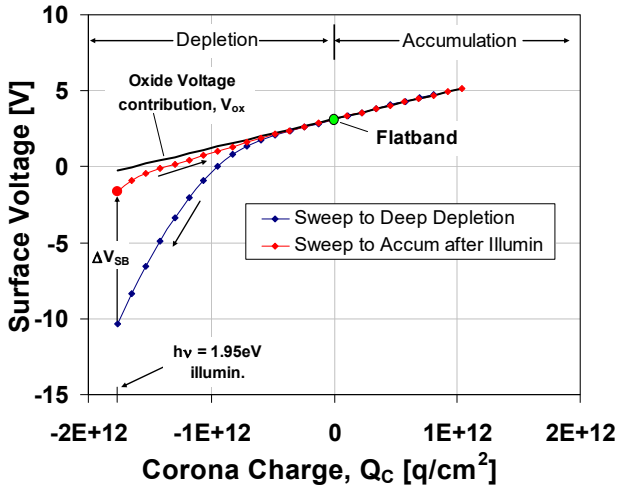

Figure 1. V-Q characteristics on n-type SiC with 45nm SiO_2. Illumination causes photoionization of interface traps.

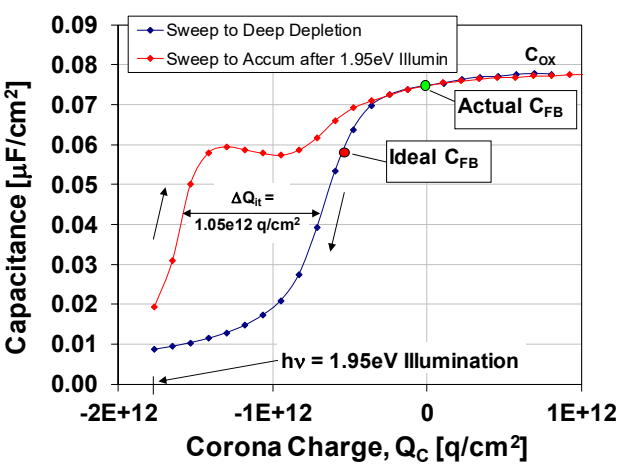

Figure 2. C-Q characteristics on n-type SiC with 45nm oxide. Photoionization of interface traps causes negative C-Q shift.

Illustrated in Fig. 3, the method uses electron photoionization transition from the interface traps in deep depletion. The process is monitored using surface voltage transients. Results in Fig. 4 are for oxidized n-type SiC illuminated in deep depletion with 635nm LED (hν = 1.95eV) illumination. The voltage saturation corresponds to empty traps and this state remains after turning the light off.

The effect of photoionization is observed in the V-Q and C-Q characteristics in Fig. 1 and 2. Emptying of traps decreases the surface barrier, but it does not affect the oxide

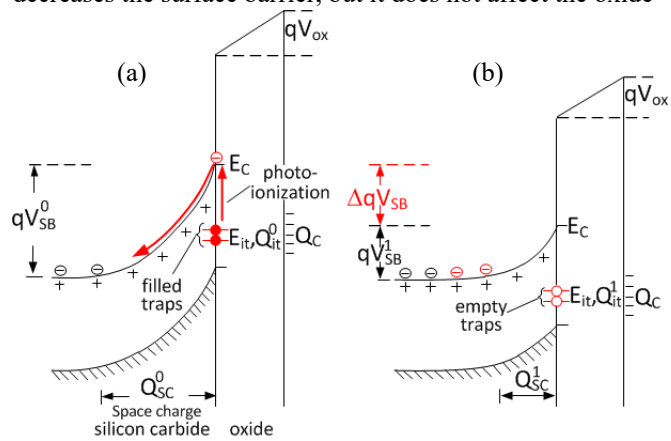

Figure 3. (a) Photoionization of deep interface traps and (b) corresponding decrease of semiconductor space charge barrier.

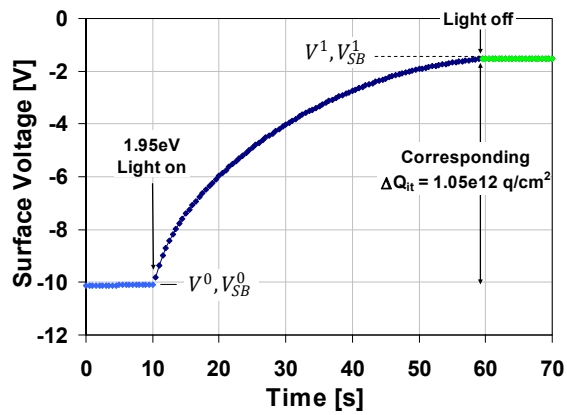

Figure 4. Surface voltage transient corresponding to Fig.1 and 2 resulting from photoionization of deep interface traps with 1.95eV illumination.

voltage or corona charge. Photon energy above the photoionization threshold, $h\nu_{threshold} = E_c - E_t$, depopulates the interfacial traps. The decrease of trapped interfacial electron charge, qn_t, is manifested by the surface voltage transients shown in Fig. 5. The transients were measured for the same photon energy hν=1.95eV, but at three different light intensities increasing from I_1 to I_3. The results indicate faster transients for higher intensities, however with the same magnitude of the surface voltage change, i.e. the same magnitude of the electron charge removed from the interfacial traps. The change of the interfacial charge is proportional to $\sqrt{V_{SB}}$. The corresponding transient data in a logarithmic scale are shown in Fig. 6. The results demonstrate an exponential time decay of the interfacial charge with photoionization time constants, τ_{ph}, ranging from 10.4s to 27s. The insert in Fig. 6 shows a linear dependence of τ_{ph}^{-1} on the illumination intensity as theoretically expected for the interfacial state photo-ionization process.

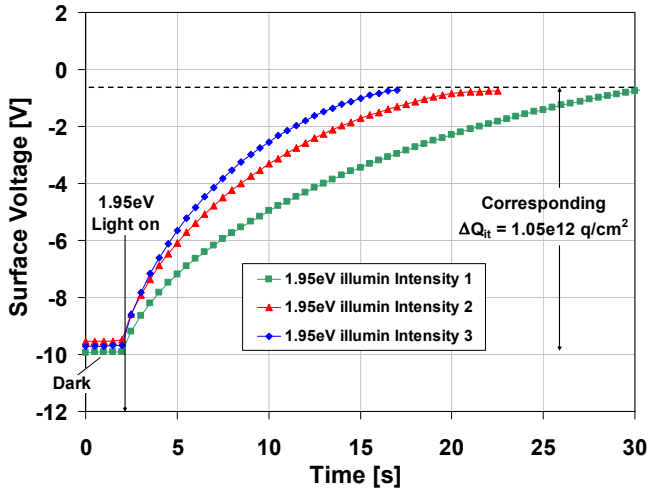

Figure 5. Surface voltage transients for n-type SiC with 45nm oxide resulting from photoionization of deep interface traps with 1.95eV illumination at three intensities increasing from I_1 to I_3.

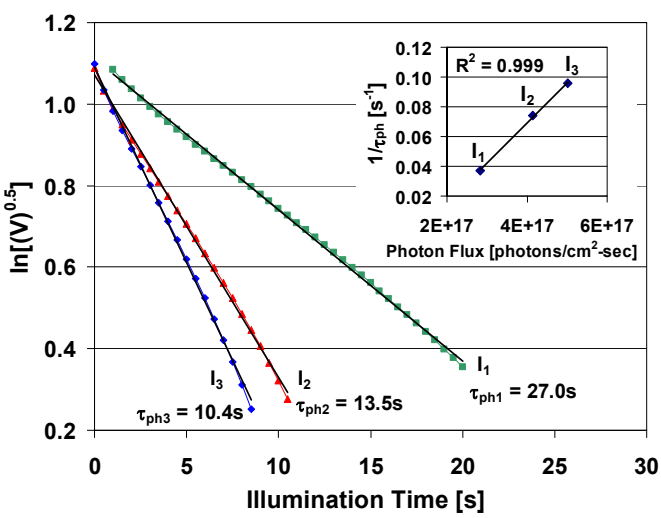

Figure 6. Surface voltage transients from Fig. 5 plotted on logarithmic scale illustrating exponential decay of interfacial trapped charge as a result with of 1.95eV illumination at various intensities. Expected linear dependence of $1/\tau_{ph}$ on illumination intensity is illustrated in the insert.

The corresponding rate equation is: $dn_t/dt = I\sigma_{in}\, n_t + I\sigma_{ip}\, p_t$. I is the incident photon flux; σ_{in} and σ_{ip} are the photoionization cross sections for electrons and holes; $p_t = N_t - n_t$ denotes the trapped holes. The rate equation includes electron transitions, $E_t \rightarrow E_C$, from the occupied trap to the conduction band and from the valence band to the empty trap, $E_V \rightarrow E_t$. Initially the $E_t \rightarrow E_C$ transition dominates because the trap is fully occupied, i.e. $n_t = N_t$ and $p_t = 0$. The valence band transition becomes possible when the trap is depopulated of electrons, producing a noticeable $p_t = N_t - n_t$. From the rate equation it follows that n_t decays exponentially from $n_t(t = 0) = N_t$ to a final value $n_t = N_t \cdot \sigma_{ip}/(\sigma_{in} + \sigma_{ip})$ that is independent of light intensity. For a process dominated by electron photoexcitation ($\sigma_{in} \gg \sigma_{ip}$) $n_t \rightarrow 0$ and total $\Delta n_t \cong N_t$. This condition seems to be the case for the present results. The ionization time constant containing two processes, $\tau_{ph}^{-1} = I\,(\sigma_{in} + \sigma_{ip})$, reduces simply to electron photoionization with $\tau_{ph}^{-1} = I\sigma_{in}$. The value of τ_{ph} for constant I and $h\nu$ serves as an identifier of the specific interfacial trap. In fact, measurements performed for two different oxides on n-type SiC summarized in Table 1 demonstrate different interfacial trap concentrations (D_{it} spectra illustrated in Fig. 7) but the same τ_{ph} value, indicating the presence of the same deep interfacial trap.

TABLE I
SUMMARY OF INTERFACIAL TRAP PARAMETERS, DOPING AND EOT FOR TWO OXIDIZED N-TYPE SIC SAMPLES

Parameter	Oxide 1/SiC	Oxide 2/SiC
Dit at V_{FB} [q/cm2-eV]	5.01E+12	3.42E+12
Dit at E_C-0.7eV [q/cm^2-eV]	1.92E+11	4.10E+10
N_{DT} at 1.95eV [cm^{-3}]	1.04E+12	7.30E+11
τ_{ph} at 1.95eV [s]	10.4	11.1
N_D [cm^{-3}]	1.02E+16	9.52E+15
EOT [nm]	44.8	33.2

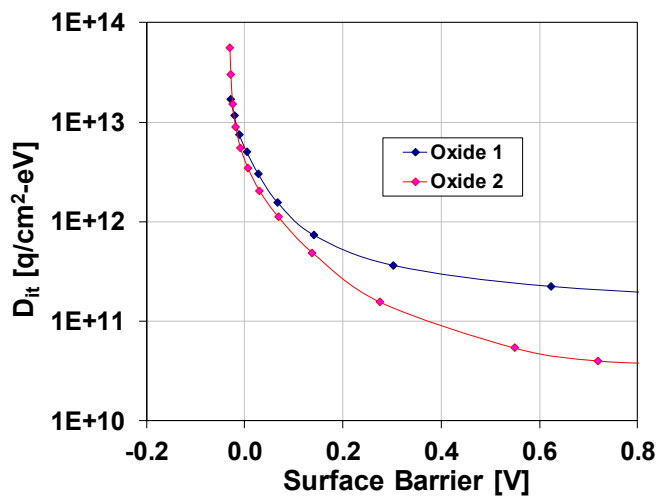

Figure 7. Interface state spectra of shallow traps for oxide 1 and 2 on n-type SiC measured with CnCV.

After photoionization the empty traps are filled with electrons during a positive corona charging sweep. C-Q sweeps after illumination for Oxide 1 and 2 are shown in Fig. 8 demonstrating negative shifts by 1.05e12 and 7.30e11 q/cm^2 for Oxide 1 and Oxide 2, respectively. The negative shifts the C-Q curves are a measure of the photoionized deep trap concentration. There is good self-consistent agreement between the trap concentration determined from the magnitude of the surface voltage change and C-Q shift after illumination. C-V curves for Oxides 1 and 2 before and after interfacial trap photoionization are illustrated in Fig. 9.

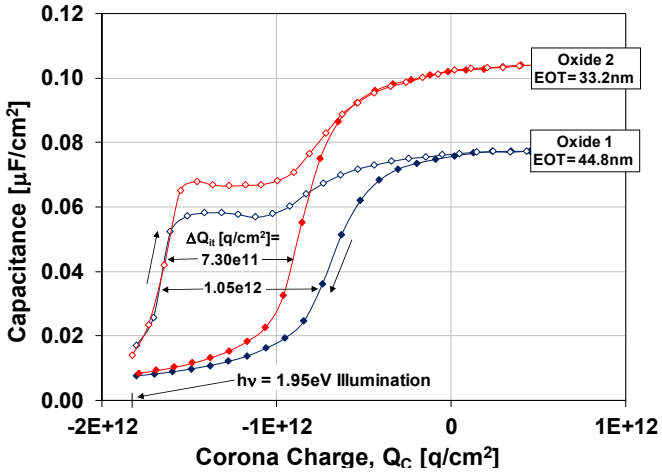

Figure 8. C-Q characteristics on oxidized n-type SiC with different deep interface trap concentrations.

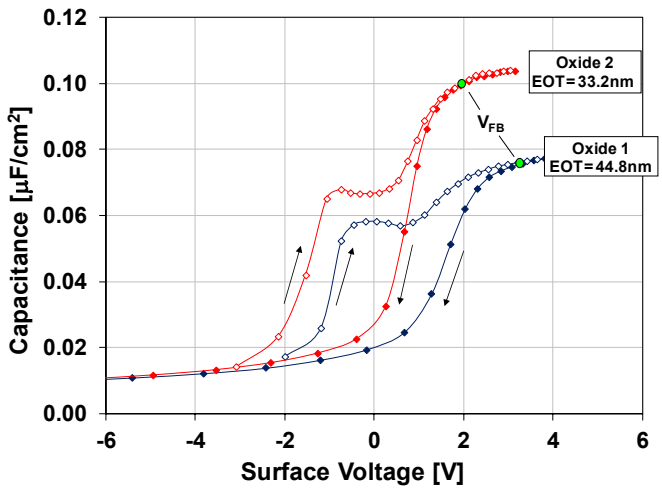

Figure 9. C-V characteristics on n-type SiC with 45nm oxide (Oxide 1) and 33nm oxide (Oxide 2) with different deep interface trap concentrations.

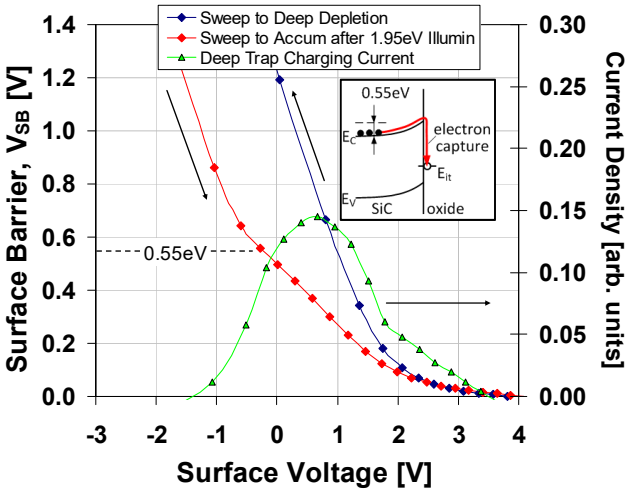

Figure 10. Filling of deep interface traps observed in surface barrier characteristics, V_{SB}-V, and trap charging current, I-V, measured with corona sweep to accumulation for oxide 1.

The refilling of the deep interfacial traps starts when the surface barrier is decreased below 0.55eV during the positive corona sweep to accumulation as illustrated in Fig. 10 for oxide 1. It is manifested by the corresponding peak in charging current.

Photoionization measurements with 1.49eV illumination (830nm wavelength) revealed negligible surface voltage transients or C-Q shifts on the oxidized SiC measured in this study. The energy estimated from the spectral threshold of photoionization is about 1.7eV below the conduction band.

Similar photo-ionization of deep interfacial traps was observed in oxidized n-type GaN as illustrated by the C-V curves in Fig. 11.

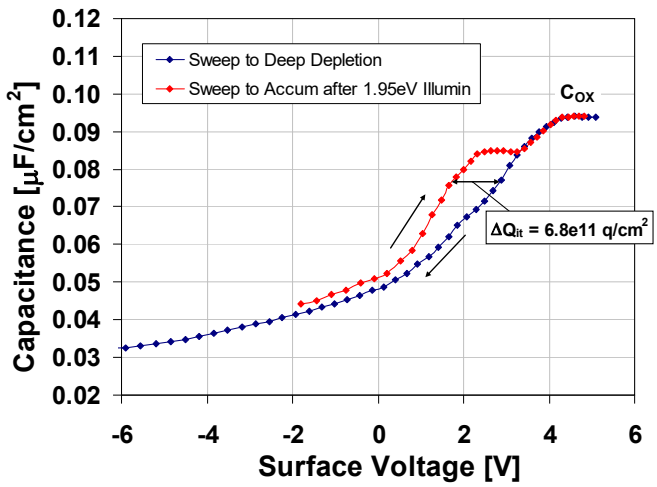

Figure 11. Corona noncontact C-V characteristics for n-type GaN with 37nm oxide illustrating photoionization of deep interfacial traps after 1.95eV illumination.

CONCLUSIONS

We present a new generation of corona noncontact C-V metrology that introduces two novel photo-assisted techniques: 1. Direct determination of V_{FB} that forms the basis of a self-consistent, multiparameter characterization of wide bandgap interfaces and 2. Characterization of deep interfacial traps that are invisible to conventional C-V using photoionization combined with corona charge biasing.

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