Mat. Res. Soc. Symp. Proc. Vol. 680E © 2001 Materials Research Society

Frequency Response of Trap States in an $Al_xGa_{1-x}N$/GaN Heterostructure Field-Effect Transistor Measured at the Nanoscale by *dC/dV* Spectroscopy

Daniel M. Schaadt and Edward T. Yu
Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, California, 92093-0407

ABSTRACT

Scanning capacitance spectroscopy has been used to characterize, at the nanoscale, the frequency-dependent response of surface charge and of charge in the two-dimensional electron gas of an $Al_xGa_{1-x}N$/GaN heterostructure field-effect transistor structure. *dC/dV* spectra were measured in a scanning capacitance microscope with a voltage signal consisting of a triangle wave at frequencies of 1 – 50 Hz applied to the sample. The spectra were obtained in the dark (except for 600 nm laser light from the scanning capacitance apparatus) and under illumination. Measurements were performed in the vicinity of and away from charged threading dislocations visible in scanning capacitance images. In the absence of illumination, the *dC/dV* data indicate that electrons are trapped at or near the $Al_xGa_{1-x}N$ surface, consistent with suggestions in the literature that a high density of surface states exists on the free $Al_xGa_{1-x}N$ surface. Frequency-dependent measurements show that emission times for these traps can be as long as several hundred ms. In the presence of illumination, reduced electron trapping is observed. The nature and behavior of trap states in the vicinity of threading dislocations is found to differ significantly from that in regions between dislocations for measurements in the dark, and suggest that the electrostatic potential due to the charged threading dislocation is negligible at the surface.

INTRODUCTION

$Al_xGa_{1-x}N$/GaN heterostructure field effect transistors (HFET's) have attracted intense research interest in recent years due to their importance for microwave and high-temperature/ high-power electronic applications. However, high-frequency operation of nitride HFET's often results in decreased power output, which is probably due to the presence of trap states [1]. It is therefore important to determine trap locations and to correlate trap levels with defects to be able to improve high-frequency operation of $Al_xGa_{1-x}N$/GaN devices. Persistent photoconductivity measurements on an $Al_xGa_{1-x}N$/GaN HFET structure have revealed defect levels with a time constant of up to a few hours, located in both the $Al_xGa_{1-x}N$ and the GaN layer [2], and gate-drain capacitance and conductance measurements have suggested the existence of traps at densities of ~ 10^{12} cm^{-2}/eV and with time constants of ~ 1 ms [3]. The location of the traps is believed to be at the heterojunction interface, in the $Al_xGa_{1-x}N$ barrier layer, and/or at the metal-semiconductor interface.

Scanning capacitance microscopy (SCM) is a powerful technique for probing nanoscale electronic properties and charge trapping effects. It has been demonstrated on a nitride HFET structure that positive charge can be trapped at the $Al_xGa_{1-x}N$ surface or within the GaN layer while negative charge can be trapped at or near the $Al_xGa_{1-x}N$/GaN interface, with trapping time constants on the order of approximately one hour [4]. We have previously used SCM and local *dC/dV* spectroscopy to image shifts in threshold voltage of an $Al_xGa_{1-x}N$/GaN HFET structure [5]. The shifts in threshold voltage were correlated to thickness and composition variations in the

$Al_xGa_{1-x}N$ layer and to the presence of charged threading dislocations. Local *dC*/*dV* spectroscopy has also been used to investigate hysteresis effects associated with charge deposition in a nitride-oxide-silicon structure [6].

In this letter, we report on the application of SCM and local *dC*/*dV* spectroscopy to characterize the frequency-dependent response of trapping of surface charge and of charge in the two-dimensional electron gas (2DEG), both in the vicinity of and away from charged threading dislocations.

EXPERIMENT

All measurements were performed with a grounded, conductive $Co_{.85}Cr_{.15}$ coated probe tip in a Digital Instruments 3100 scanning capacitance microscope under ambient conditions with bias applied to ohmic contacts on the sample. The sample used in these studies consisted of a 23 nm undoped $Al_{.26}Ga_{.74}N$/ GaN heterostructure grown by metal organic chemical vapor deposition. A detailed sample description is given elsewhere [5].

To obtain local *dC*/*dV* spectra, we reduced the scan area to 1 nm × 1 nm and recorded the SCM signal, which is proportional to the derivative of the tip-sample capacitance. The spectra were obtained as a function of tip-sample bias, with the applied voltage signal consisting of the internal SCM high-frequency AC bias modulation (0.25 V amplitude at 100 kHz) and an externally applied triangle wave bias V_{Sample}, which was ramped from -6 to 6 V (forward-to-reverse bias) and from 6 V to –6 V (reverse-to-forward bias), at frequencies of 1 - 50 Hz. To reduce noise, we recorded and averaged multiple *dC*/*dV* versus V_{Sample} curves for the forward-to-reverse and reverse-to-forward ramp directions separately. Spectra were obtained in the dark (except for 600 nm laser light from the scanning capacitance apparatus) and in the presence of illumination with white light containing ultraviolet components. Measurements were performed in a location with no apparent contrast in SCM images (denoted in the following as background location) and in the vicinity of a charged threading dislocation, as determined from contrast variations in SCM images [5].

RESULTS AND DISCUSSION

Figure 1(a) shows *dC*/*dV* measurements obtained at the background location in the dark. When V_{Sample} is ramped from forward to reverse bias, one peak is observed (top). Due to the polarization field in the strained $Al_xGa_{1-x}N$ layer, a 2DEG is created at zero bias at the $Al_xGa_{1-x}N$/GaN interface, even in the absence of intentional doping [7]. The observed peak therefore corresponds to a change in capacitance associated with the transition from accumulation in the 2DEG (negative sample bias) to depletion (positive sample bias). The peak position remains nearly constant as the ramp frequency is varied. When V_{Sample} is ramped from reverse to forward bias, two peaks are observed (bottom). The peak at more positive sample bias can be attributed to the above-mentioned depletion of the 2DEG charge. The second peak at more negative sample bias is interpreted as a result of filling of depleted states at or near the $Al_xGa_{1-x}N$ surface [4] that were slowly emptied, and thereby not resulting in a peak, in the preceding forward-to-reverse ramp bias. This is consistent with suggestions in the literature that a high density of surface states exists on the free $Al_xGa_{1-x}N$ surface in GaN, and that those surface states can trap electrons [8,9]. In contrast to the behavior observed for the forward-to-reverse ramp, the peak positions shift monotonically with ramp frequency, indicating trapping

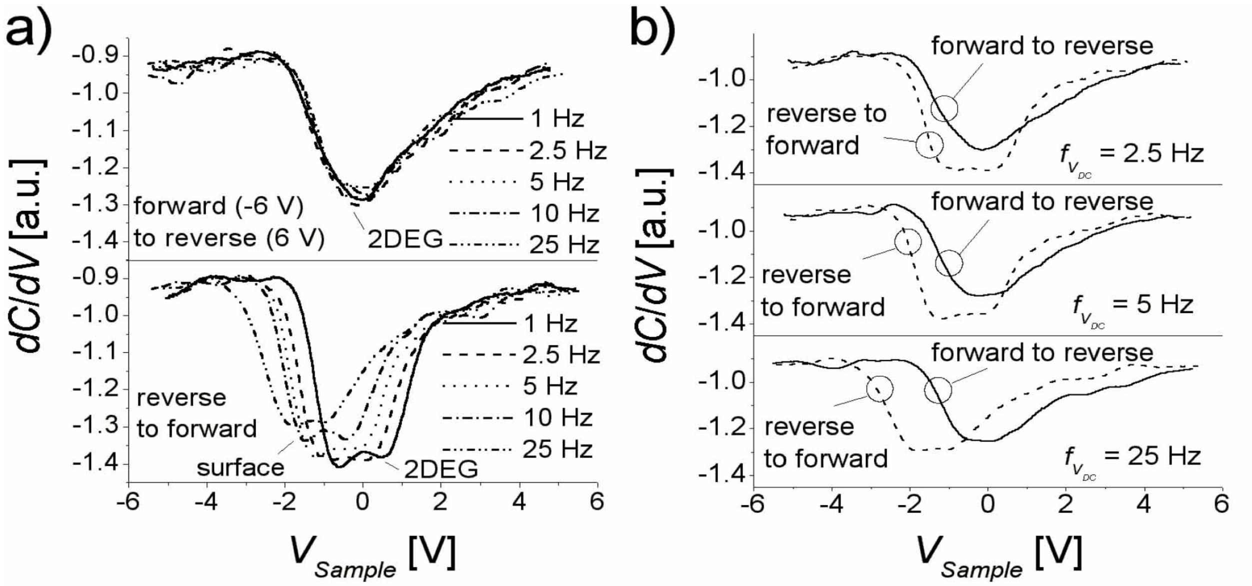

Figure 1. (a) *dC*/*dV* spectra obtained with bias ramped from forward to reverse (top) and from reverse to forward (bottom) for a range of ramp frequencies measured in darkness. (b) Hysteresis effect in *dC*/*dV* spectra taken with bias ramped from forward to reverse and vice versa.

time constants on the order of hundreds of ms. The resulting hysteresis in the *dC*/*dV* data obtained for both ramp directions is shown in Figure 1(b) for selected ramp frequencies. Figure 1(b) shows clearly that the hysteresis effect becomes larger with increasing ramp frequency.

Figure 2 shows corresponding *dC*/*dV* data taken at the background location under illumination. In contrast to the measurements in the dark, two peaks are observed when V_{Sample} is ramped from forward to reverse bias, thus indicating that surface charge is modulated.

Plots of the peak position due to depletion of 2DEG charge and charge at the surface are shown as a function of ramp frequency in Figure 3(a) and Figure 3(b), respectively. If the ramp direction is changed from forward-to-reverse to reverse-to-forward, the peak position due to

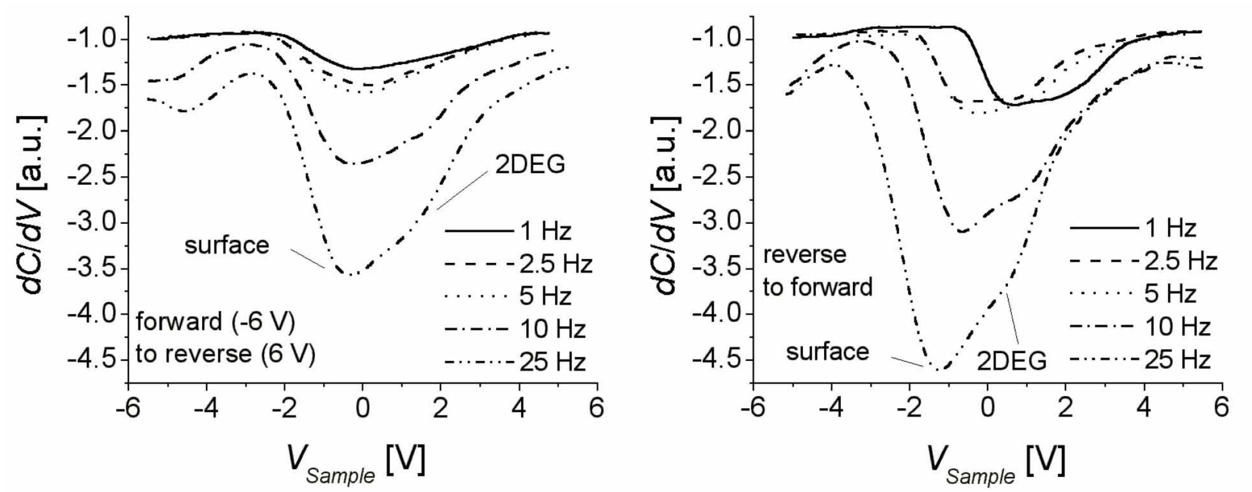

Figure 2. *dC*/*dV* spectra obtained with bias ramped from forward to reverse (left-hand side) and from reverse to forward (right-hand side) for a range of ramp frequencies measured under UV illumination.

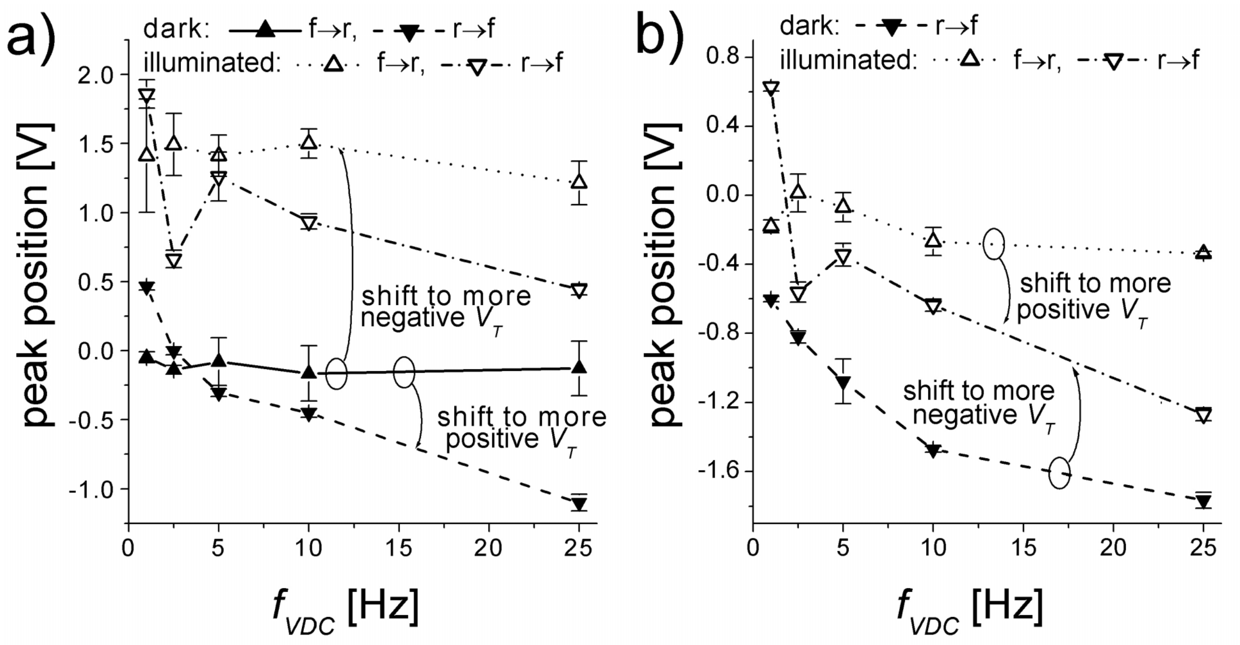

Figure 3. (a) Plots of the peak positions due to charge in the 2DEG as a function of ramp frequency for forward-to-reverse (f→r) and reverse-to-forward (r→f) direction, measured in darkness and with illumination. (b) Corresponding plots for charge at the $Al_xGa_{1-x}N$ surface.

2DEG charge shifts to more negative values, which corresponds to a shift to more positive threshold voltage V_T [5], indicating a reduction in 2DEG charge due to electron capture by traps [8,9]. The hysteresis in peak position becomes larger with increasing ramp frequency, consistent with the above mentioned trapping time constants on the order of hundreds of ms. Upon illumination, the peak position shifts to more positive values, corresponding to a shift to more negative V_T, which indicates an increase in electron concentration in the 2DEG. This can be explained by the electron-hole-pair generation due to illumination and by reduced electron capture by trap states. This is also confirmed by a smaller hysteresis at high ramp frequencies. The comparison of peak positions versus ramp frequencies for charge at the surface, shown in Figure 3(b), indicates that surface charge exhibits the same behavior as the charge in the 2DEG with changes in ramp frequencies and upon illumination.

dC/*dV* spectra that were measured in the vicinity of a charged threading dislocation in the dark and under illumination are shown in Figure 4(a) and Figure 4(b), respectively. One peak is observed for measurements performed in the dark for both ramp directions. In contrast, two peaks are observed in measurements under illumination.

A comparison of the peak positions as a function of ramp frequency for measurements in the dark at the background location and in the vicinity of the charged threading dislocation is shown in Figure 5(a). The peak positions for measurements in the vicinity of the dislocation are shifted to more positive values, which correspond to higher electron concentration. However, previous measurements have shown that charged threading dislocations cause shifts to more positive V_T, i.e. lower electron concentration in the 2DEG, due to the additional potential of the charged dislocation [5].Thus, we conclude that the observed single peak does not correspond solely to charges at the surface or in the 2DEG, but might be related to the response of trap states associated with the charged threading dislocation.

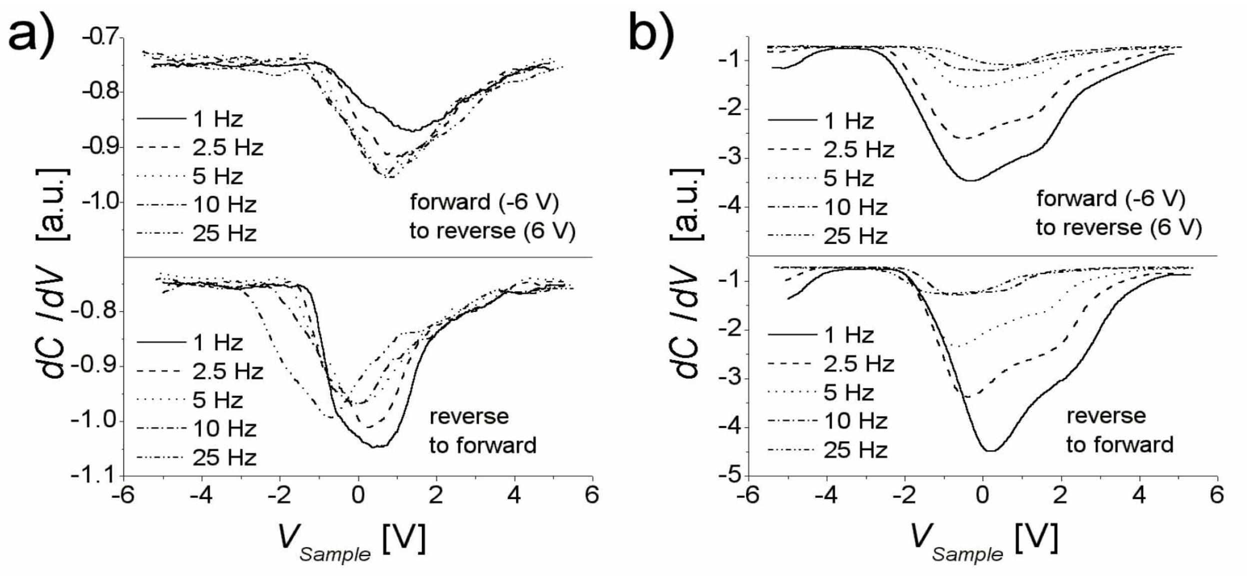

Figure 4. (a) *dC*/*dV* spectra measured in the vicinity of a charged threading dislocation in darkness and (b) under illumination.

In contrast, the measured *dC*/*dV* spectra with illumination near the charged threading dislocation are similar to those recorded on the background location. The peak due to charges in the 2DEG, shown in Figure 5(b), shifts to more negative values, corresponding to more positive V_T, as expected from previous measurements [5]. On the other hand, the peak due to charges at the surface, shown in Figure 5(c), does not shift, indicating that the effect of the threading dislocation on charges at the surface is small. This is consistent with measurements performed on threading dislocations in GaN by ballistic electron emission microscopy, which show a negligible electrostatic potential of the threading dislocation at the surface [10].

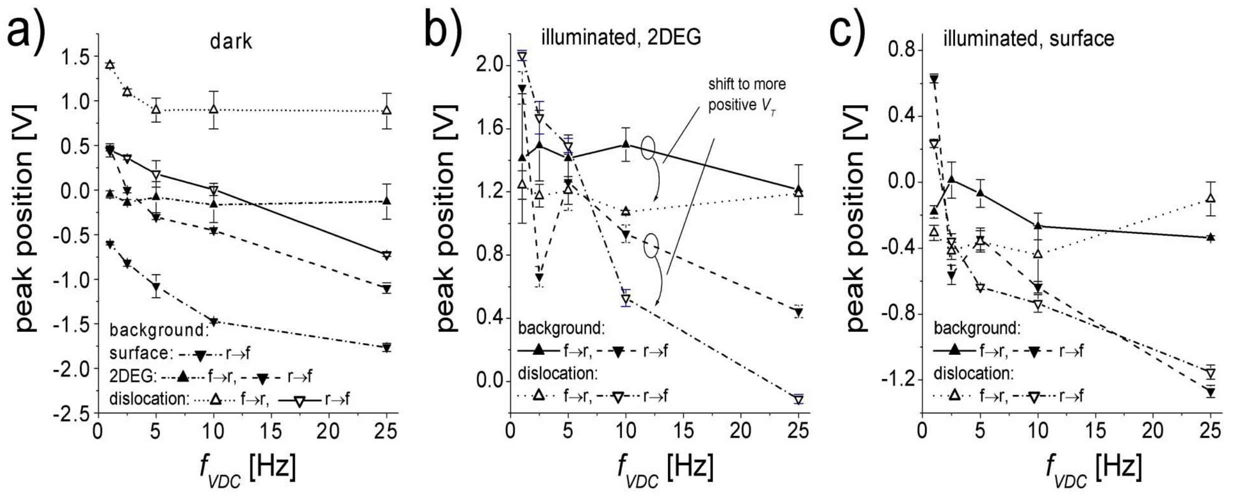

Figure 5. Comparison of peak positions versus ramp frequency for measurements performed on a background location and in the vicinity of a charged threading dislocation. (a) Measurements performed in the dark. (b) Peak due to 2DEG measured under illumination. (c) Peak due surface charge under illumination.

CONCLUSIONS

SCM and local *dC*/*dV* spectroscopy have been used to characterize the frequency-dependent response of surface charge and of charge in the 2DEG in an $Al_xGa_{1-x}N$/GaN HFET structure. *dC*/*dV* spectra were measured as functions of tip-sample bias voltage near a threading dislocation visible in SCM images and at a location with no apparent SCM contrast (background location). The observed *dC*/*dV* spectra measured on the background location indicate that electrons are trapped at or near the $Al_xGa_{1-x}N$ surface and at the $Al_xGa_{1-x}N$/GaN interface. Emission times for these traps can be as long as several hundred ms. Measurements under illumination in the vicinity of a threading dislocation show a shift to more positive transistor threshold voltage consistent with a local depletion of charge due to the additional potential of the charged threading dislocation. In the absence of illumination, the nature and behavior of trap states in the vicinity of threading dislocations is found to differ significantly from that on the background location, and suggest that the electrostatic potential due to the charged threading dislocation is negligible at the surface.

ACKNOWLEDGMENTS

The authors thank Dr. X. Z. Dang for help in the fabrication of the ohmic contacts, and Prof. H. H. Wieder for useful discussions. We acknowledge Prof. J. M. Redwing (PennState University) for providing the epitaxial wafer used in these studies. Part of this work was supported by ONR under Grant Nos. N00014-99-1-0729 (POLARIS MURI, Dr. Colin Wood) and N00014-99-1-0545 (DURIP, Dr. John Zolper) and by NSF under Grant. No. DMR-0072912.

REFERENCES

1. E. Kohn, I. Daumiller, P. Schmid, N. X. Nguyen, and C. N. Nguyen, *Electron. Lett.* **35**, 1022 (1999)
2. X. Z. Dang, C. D. Wang, E. T. Yu, K. S. Boutros, and J. M. Redwing, *Appl. Phys. Lett.* **72**, 2745 (1998)
3. E. J. Miller, X. Z. Dang, H. H. Wieder, P. M. Asbeck, E. T. Yu, G. J. Sullivan, and J. M. Redwing, *J. Appl. Phys.* **87**, 8070 (2000)
4. K. V. Smith, X. Z. Dang, E. T. Yu, and J. M. Redwing, *J. Vac. Sci. Technol. B* **18**, 2304 (2000)
5. D. M. Schaadt, E. J. Miller, E. T. Yu, and J. M. Redwing, *Appl. Phys. Lett.* **78**, 88 (2001); submitted to *J. Vac. Sci. Technol. B* (2001)
6. R. C. Barrett and C. F. Quate, *J. Appl. Phys* **70**, 2725 (1991)
7. A. Bykhovski, B. Gelmont, and M. Shur, *J. Appl. Phys.* **74**, 6734 (1993)
8. S. Trassaert, B. Boudart, C. Gaquière, D. Théron, Y. Crosnier, F. Huet, and M. A. Poisson, *Electron. Lett.* **35**, 1386 (1999)
9. S. C. Binari, K. Ikossi, J. A. Roussos, W. Kruppa, D. Park, H. B. Dietrich, D. D. Koleske, A. E. Wickenden, and R. L. Henry, *IEEE Trans. Electron Devices* **48**, 465 (2001)
10. H. –J. Im, Y. Ding, J. P. Pelz, B. Heying, and J. S. Speck, presented at the 28th Conference on the Physics and Chemistry of Semiconductor Interfaces, Lake Buena Vista, FL, 2001