Scanning capacitance spectroscopy and quantitative analysis of lateral threshold voltage variations in an $Al_xGa_{1-x}N/GaN$ heterostructure field-effect transistor

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1. Introduction

- $Al_xGa_{1-x}N/GaN$ heterostructure field effect transistors (HFET's) have attracted intense research interest due to their importance for microwave and high-temperature/high-power electronic applications.

- Significant lattice mismatch between GaN and commonly used substrates such as sapphire or SiC results in high threading dislocation densities (~ 10^8 – 10^{10} cm^{-2}), which can lead to increased carrier scattering and high concentrations of acceptor-like trap levels.

- Hansen et al. [APL 72, 2247 (1998)] demonstrated that the HFET threshold voltage V_T can shift by up to 1.5 V near a dislocation.

- Presence of thickness and composition variations in the $Al_xGa_{1-x}N$ layer can result in further variations in V_T [Smith et al., APL 75, 2250 (1999), Smith et al., JEM 29, 274 (2000)].

- However, only limited quantitative experimental information is available to directly correlate shifts in threshold voltage with threading dislocations, thickness and composition variations, and other defects.

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Perform local *dC/dV* spectroscopy to map, quantitatively and with high spatial resolution (~ 50 nm), lateral variations in the threshold voltage

2. Experimental Procedure

Sample

- $Al_xGa_{1-x}N$/GaN heterostructure grown by MOCVD
- 33 nm Ti/77 nmAl ohmic contacts (annealed at 750 C for 1.5 min)
- Two-dimensional electrongas is created at zero bias at the $Al_xGa_{1-x}N$/ GaN interface due to polarization field in the strained $Al_xGa_{1-x}N$ layer

23 nm $Al_{.26}Ga_{.74}N$
1.2 μm undoped - GaN
AlN buffer layer
4H-SiC substrate

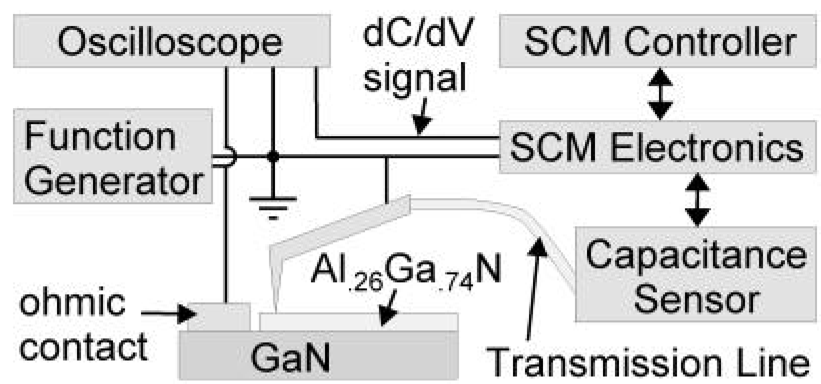
Setup and measurement procedure

Use of scanning capacitance microscope

1) Aquire topography and scanning capacitance images with a highly doped p^+ - type Si tip

2) Local *dC*/*dV* spectroscopy

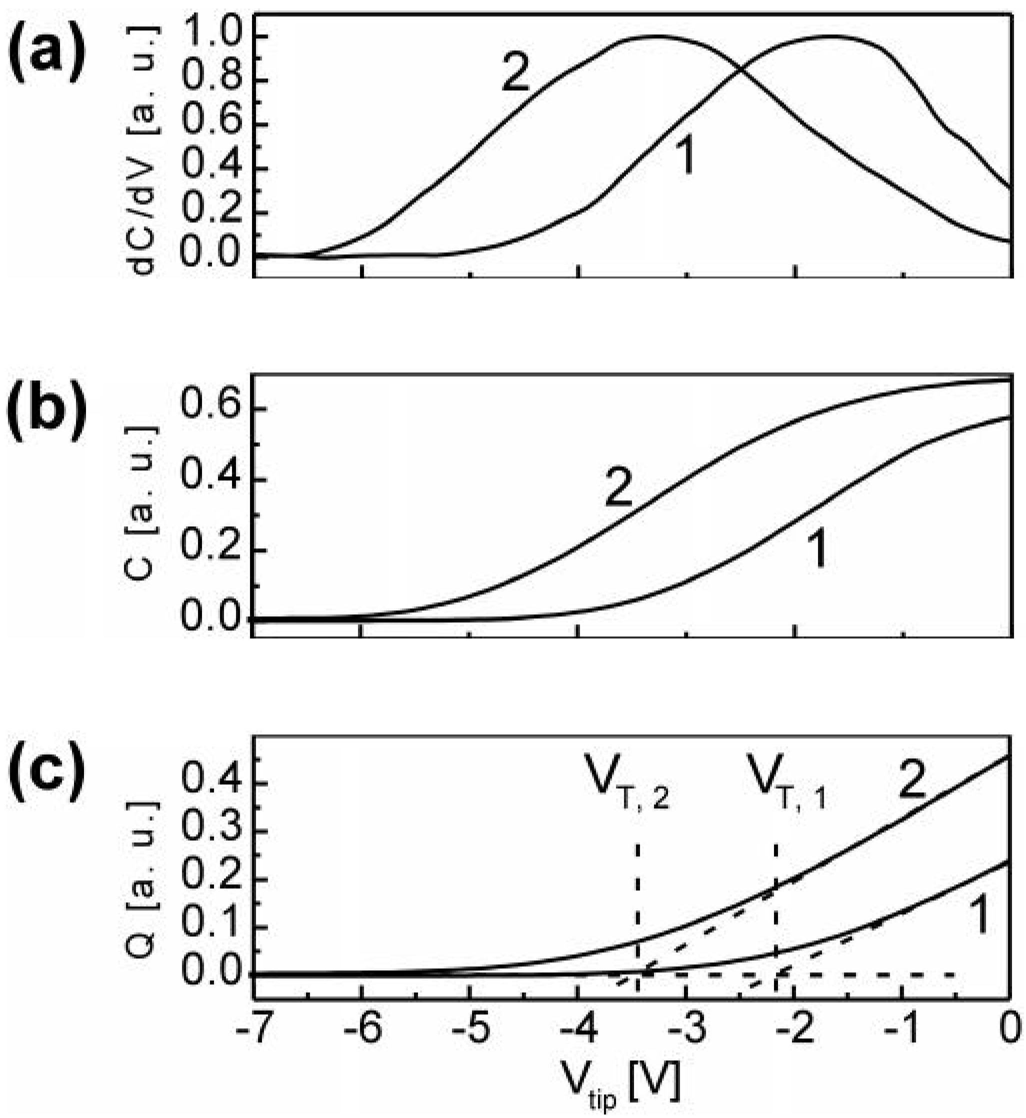
- Move tip to measurement location and reduce scan area to 1 × 1 nm² (small area scan, high resolution) or 10 × 10 nm² (large area scan, low resolution)



- Apply internal AC tip-sample bias voltage (V_{AC} = 2 V, f_{AC} = 100 kHz)
- Add external DC bias consisting of a triangle wave at a frequency of 5 Hz
- Record and average multiple (typically 50-400) *dC*/*dV* versus *V* curves
- move tip to successive positions in steps of 50 nm or 1 μm and repeat procedure

2. Experimental Procedure

Data processing and analysis



Normalize data

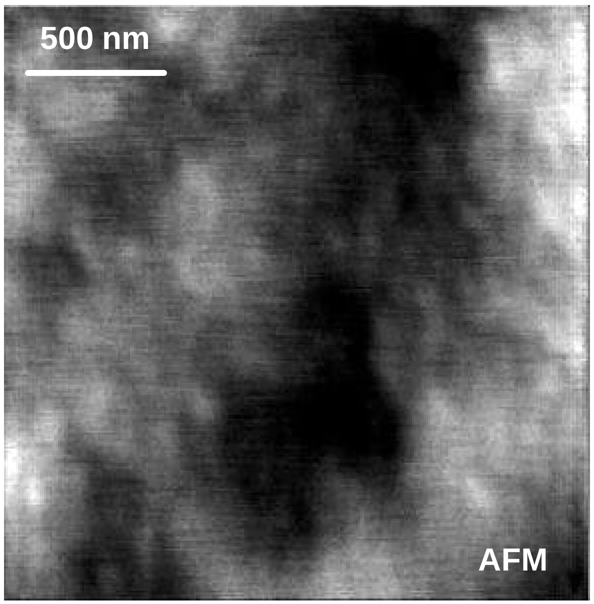
Integrate to obtain *C* - *V* curve

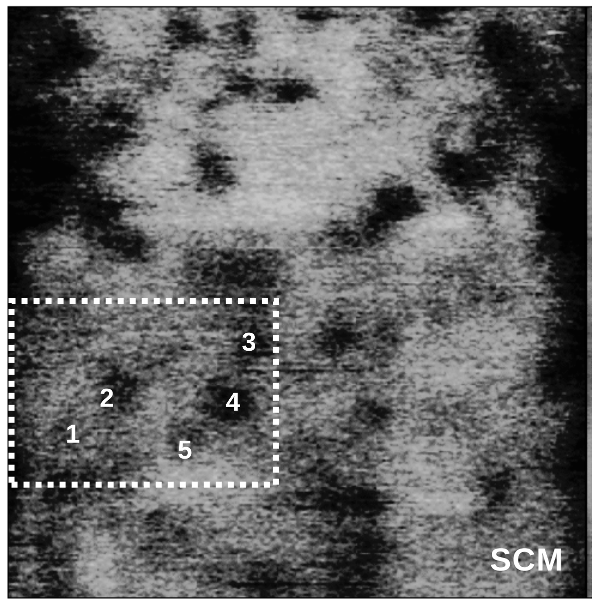
Integrate again to obtain charge as a function of applied bias

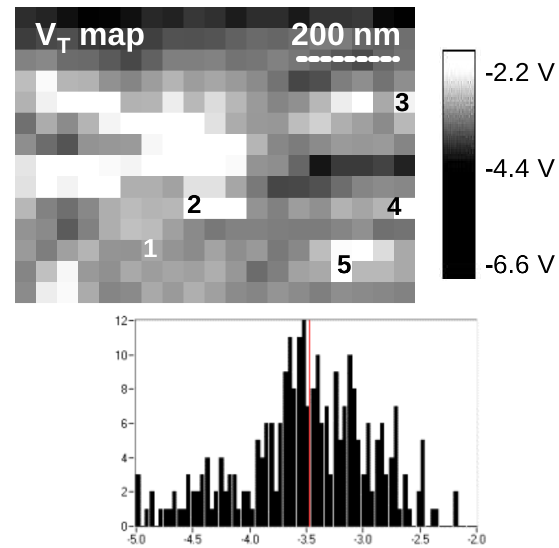
V_T is obtained by linear extrapolation to $Q = 0$ in the Q - V plot

3. Results and Discussion

Effects of threading dislocations on V_T







$V_T = -3.5 \pm 0.6$ V

- No direct correlation between topography and SCM possible
- SCM image shows small (~ 100 - 150 nm in diameter) round features with a threshold voltage shift of about 1.5 – 2 V compared to the average threshold voltage
- Round feature are believed to be threading dislocations

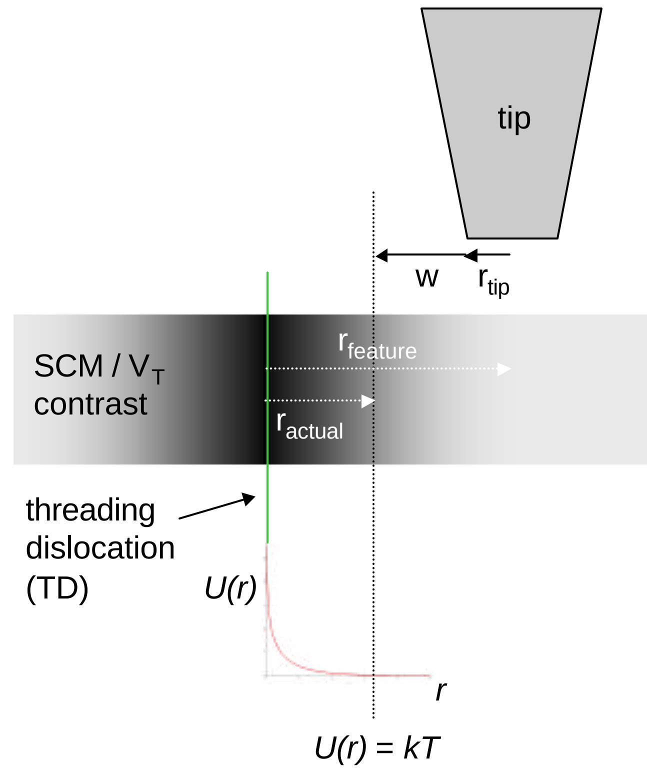
3. Results and Discussion

<u>Observed feature radius</u>: $r_{feature} \approx 50 - 75$ nm

Assume radius of curvature: $r_{tip} \approx 15$ nm

Convolution with tip shape: $r_1 = r_{feature} - r_{tip} \approx 35 - 60$ nm

Effect of depletion region $w \approx 30$ nm: $r_{actual} = r_1 - w \approx 5 - 30$ nm



Potential due to continuously charged line with line charge density γ, assuming cylindrical symmetry and screening by ionized impurities and free electrons [B. Pödör, P. Stat. Sol. B 16, K167 (1966)]:

$$U(r) = \frac{1}{4pee_0} 2qg\, K_0\left(\frac{r}{l_D}\right) \quad \text{with Debye length} \quad l_D = \sqrt{\frac{kTee_0}{q^2 N_d}}$$

(K_0 = modified Bessel function of the second kind of zeroth order)

$g = f/c$ where f is the fraction of filled traps and c the [0001] lattice constant of $Al_xGa_{1-x}N$

for TD density of $10^9 cm^{-2}$ and $N_d = 10^{18} cm^{-3}$: $f \approx 0.5$ and $l_D \approx 3.5$ nm [Weinmann et al., JAP 83, 3656 (1998)]

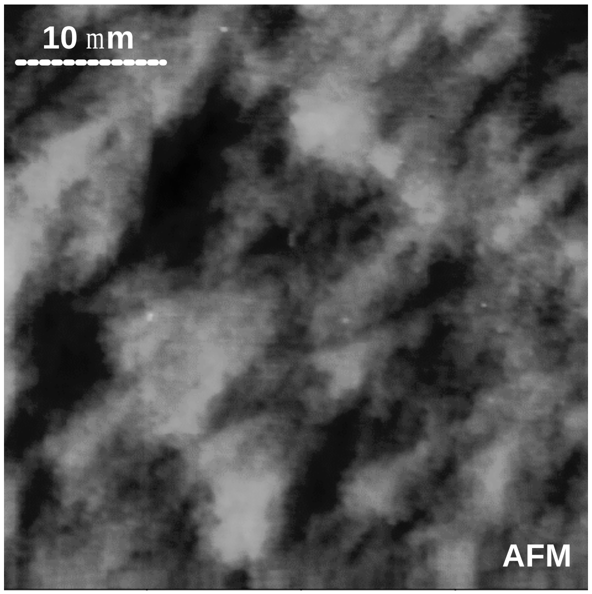
$U(r) \approx kT$ for $r \approx 3.5\ l_D = 11$ nm, in good agreement with above $r_{actual} \approx 5 - 30$ nm

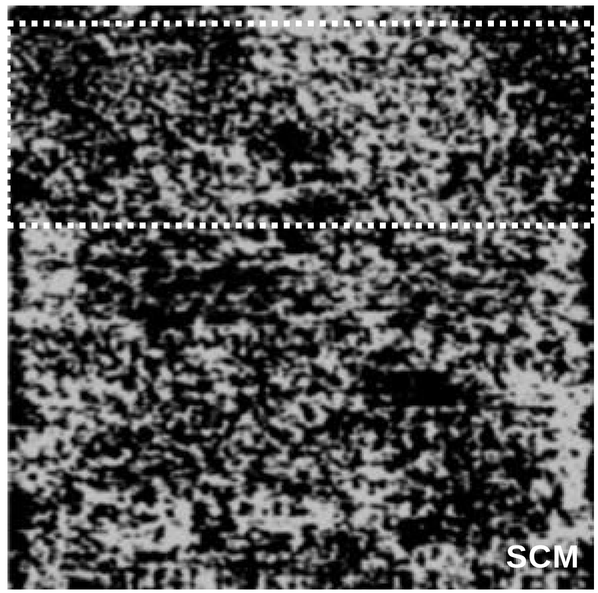
<u>Observed threshold voltage shift over TD</u>: $DV_T \approx 1.5$ V - 2 V

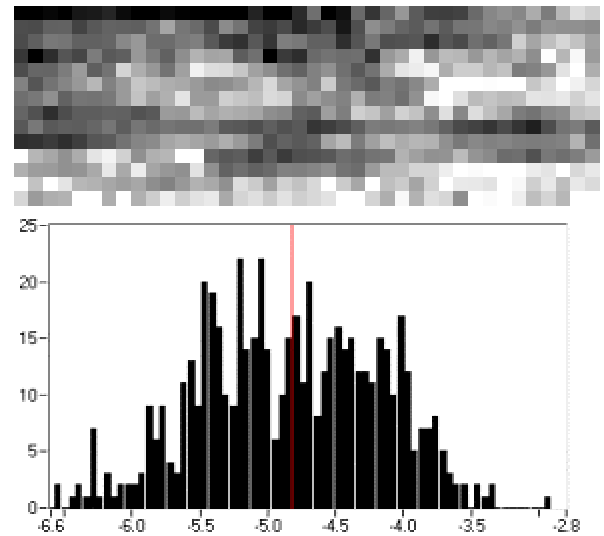
$Q = -C\, DV_T \approx -3.4\times10^{-12}\ e/cm^2$ — $-4.6\times10^{-12}\ e/cm^2$ ≈ amount of charge expected to be contained, within the $Al_xGa_{1-x}N$ barrier layer and an area equal to the tip size, on a threading dislocation with linear charge density g

3. Results and Discussion

Effects of thickness and compositional variations on V_T







$V_T = -4.8 \pm 0.7$ V

- No direct correlation between features observed in topography and SCM images
- Threshold voltage map shows large (~ 3 - 7 mm) features at length scales consistent with those observed in the corresponding topography and SCM scans

3. Results and Discussion

Electron sheet concentration in the 2DEG of the $Al_xGa_{1-x}N$/GaN HFET
[Yu et al., JVST B 17, 1742 (1999)]:

$$n_s = \frac{s_{pol}}{q} - \frac{e_0 e}{d e^2}\left(f_b + \frac{E_F - \Delta E_C}{q} + V\right) + \frac{1}{2} N_d d$$

with s_{pol} polarization sheet charge density at the heterojunction interface

Threshold voltage can be calculated if n_s = 0: $V_T = -f_b - \frac{E_F - \Delta E_C}{q} + \frac{s_{pol}\, d}{e_0 e} + \frac{N_d\, q\, d^2}{2 e_0 e}$

Thickness variations: $\Delta V_T \approx \frac{s_{pol} + q N_d d}{e_0 e} \Delta d$ for $\Delta d << 2d$

for an Al concentration of 26% and a layer thickness d = 23 nm: $s_{pol} \approx 1.25 \times 10^{13}$ e/cm^2
$\rightarrow DV_T \approx$ 0.25 V for a thickness change of about Dd = 1 nm

Composition variations: $\Delta V_T = \frac{d}{e_0 e} \Delta s_{pol} \approx 25\, \Delta x$ V

relative composition variation of about 5 % ($Dx \approx$ 0.01) yields a change in threshold voltage comparable to that of a 1nm thickness variation

$\Rightarrow$ The observed larger variations in of more than 1 V might therefore be consequence of a combination of thickness and composition variations in the $Al_xGa_{1-x}N$ layer.

4. Conclusions

Local dC/dV spectroscopy was performed in a SCM to quantify and map lateral variation in the threshold voltage of an $Al_xGa_{1-x}N$/GaN HFET structure

- The local threshold voltage was extracted by linear extrapolation of the charge in the 2DEG of the HFET to zero charge, which was obtained by double-integration of the dC/dV data

- Small (~ 100 - 150 nm in diameter) round features which show a threshold voltage shift of about 1.5 – 2 V compared to the average threshold voltage, and larger features several µm in size with corresponding threshold voltage shifts of up to 1 V or more were observed

- The small features exhibit approximate charge densities consistent with the presence of charged threading dislocations that cause localized reduction or depletion of carriers from the 2DEG

- The larger features are postulated to arise from a combination of thickness and composition variations in the $Al_xGa_{1-x}N$ layer

Detailed information and further analysis can be found on the poster!