Frequency response of trap states in an $Al_xGa_{1-x}N$/GaN heterostructure field-effect transistor (HFET) measured at the nanoscale by *dC*/*dV* spectroscopy

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Outline

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- Results and discussion
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Motivation

- $Al_xGa_{1-x}N$/GaN heterostructure field effect transistors (HFET's) have attracted intense research due to importance for microwave and high-temperature/high-power electronic applications.
- Decreased power output in high-frequency operation of nitride devices, probably due to presence of trap states [Kohn et al., *Electron. Lett.* **35**, 1022 (1999)].
- Traps with long time constants have been found and investigated by persistent photoconductivity and gate-drain capacitance/conductance measurements [Dang et al., *APL* **72**, 2745 (1998), Miller et al., *JAP* **87**, 8070 (2000)].
- SCM and local dC/dV spectroscopy studies on AlGaN/GaN heterostructures indicate:
  - Charging effects [K. V. Smith et al., *J. Vac. Sci. Technol. B* **18**, 2304 (2000)].
  - Shift in V_T by up to 1.5 V near a dislocation [Hansen et al., *APL* **72**, 2247 (1998), Schaadt et al., *APL* **78**, 88 (2001)].
  - 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), *JEM* **29**, 274 (2000), Schaadt et al., submitted to *J. Vac. Sci. Technol. B* (2001)].
- SCM and local *dC*/*dV* spectroscopy have also been used to investigate charge deposition in a nitride-oxide-silicon structure [Barret et al., *JAP* **70** (1991)].

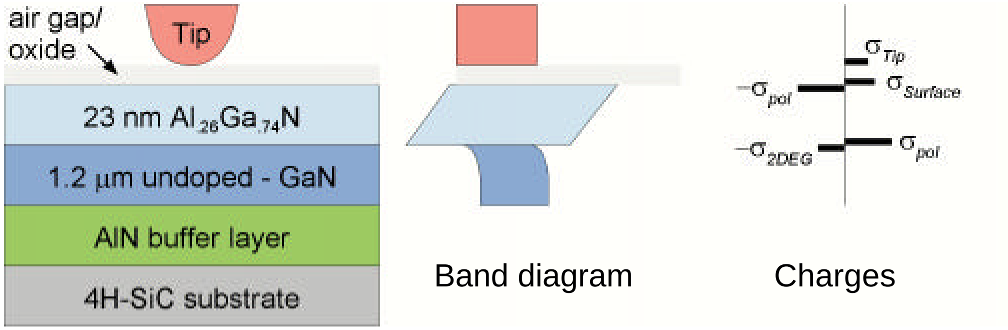
⇓

Use SCM and local *dC*/*dV* spectroscopy to characterize the frequency-dependent response of surface charges and of charges in the 2DEG with and without illumination, and to correlate traps with the nanoscale defect structure.

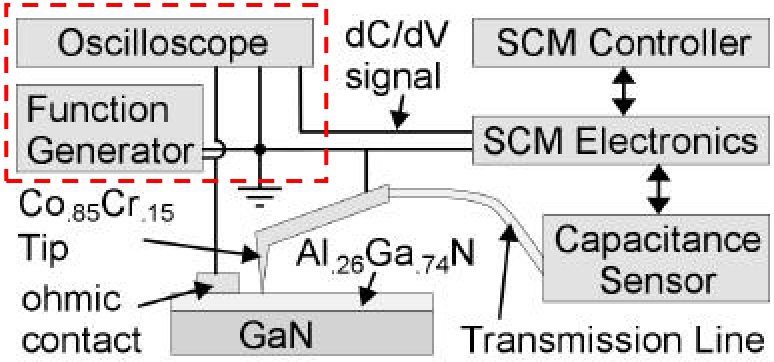
Local *dC*/*dV* spectroscopy

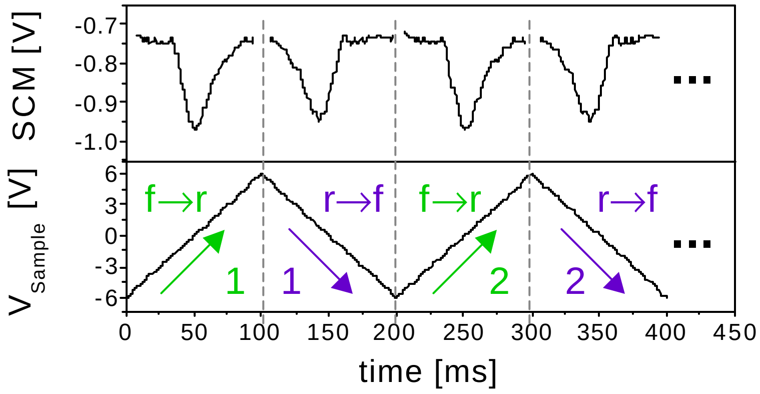
Sample:

$Al_xGa_{1-x}N$/GaN heterostructure
grown by MOCVD



Setup and measurement procedure

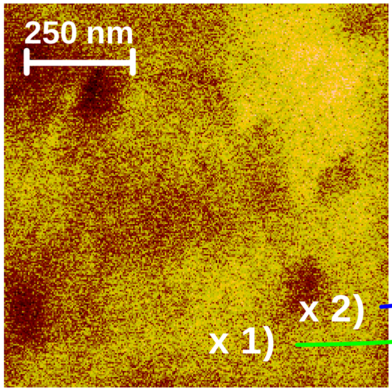




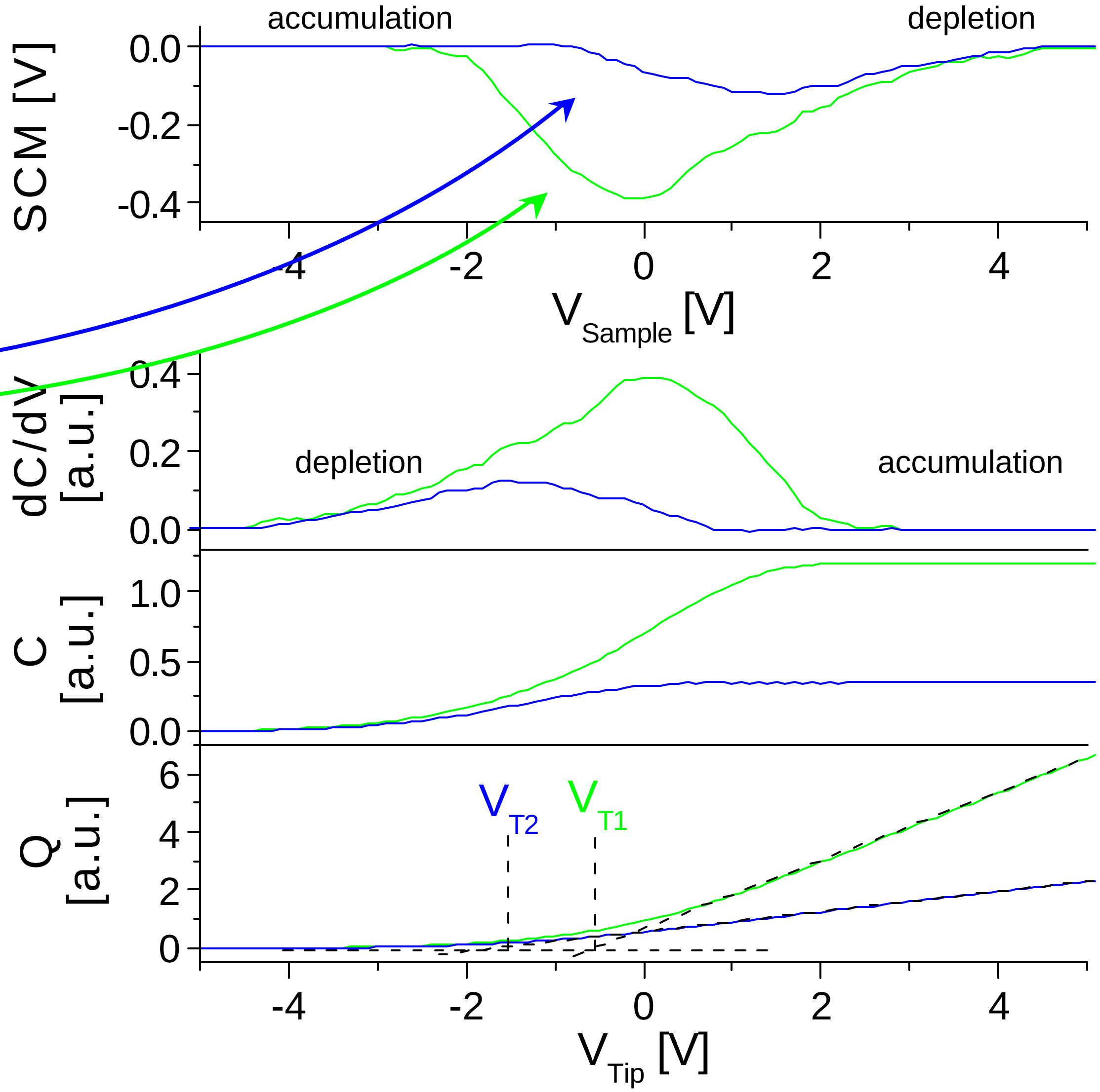
- Use modified scanning capacitance microscope (SCM)
- Local *dC*/*dV* spectroscopy:
  - Move tip to measurement location and reduce scan area to 1 nm × 1 nm
  - Apply tip-sample bias voltage consisting of:
    - internal SCM AC bias (V_{AC} = 0.25 V, f_{VAC} = 100 kHz)
    - external triangular bias ramp (V_{DC}= 6 V, f_{VDC} = 1 - 50 Hz)
  - SCM signal ∝ *dC*/*dV*
  - Record and average SCM signal vs. V_{DC} curves for:
    - forward (-6 V) to reverse bias (6 V), denoted as f→r
    - reverse to forward bias, denoted as r→f

Local *dC*/*dV* spectroscopy

Relation between SCM signal and *C*-*V* curve



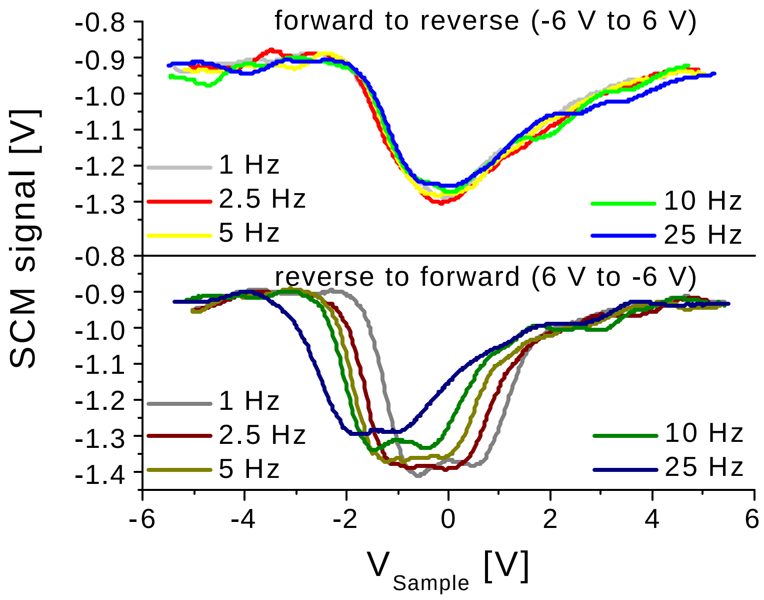
SCM: z range: 1 V, V_{Sample} = 5 V
local *dC*/*dV*: f_{VDC} = 1 Hz, ftr, dark

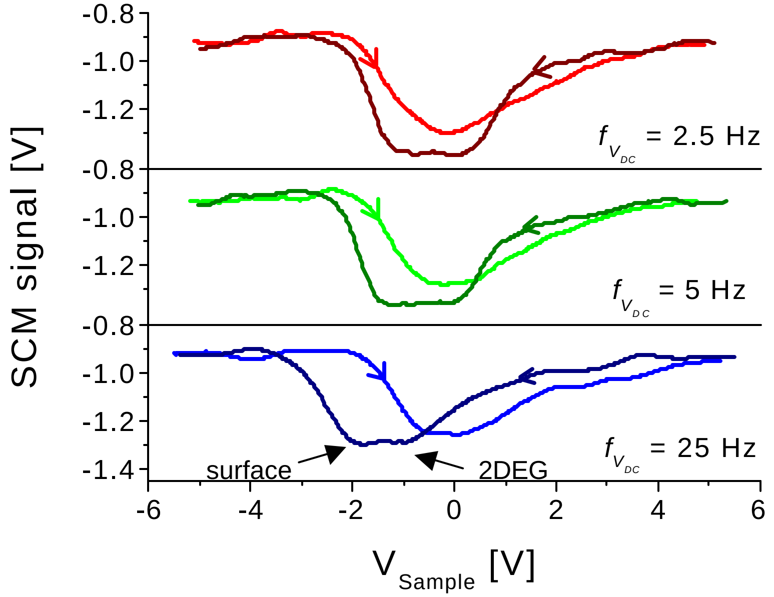


1) Background location
2) Near dislocation

Round (dark) features in SCM image are due to negatively charged threading dislocations
[Schaadt et al., *APL* **78**, 88 (2001)]

dC/dV on background location, dark



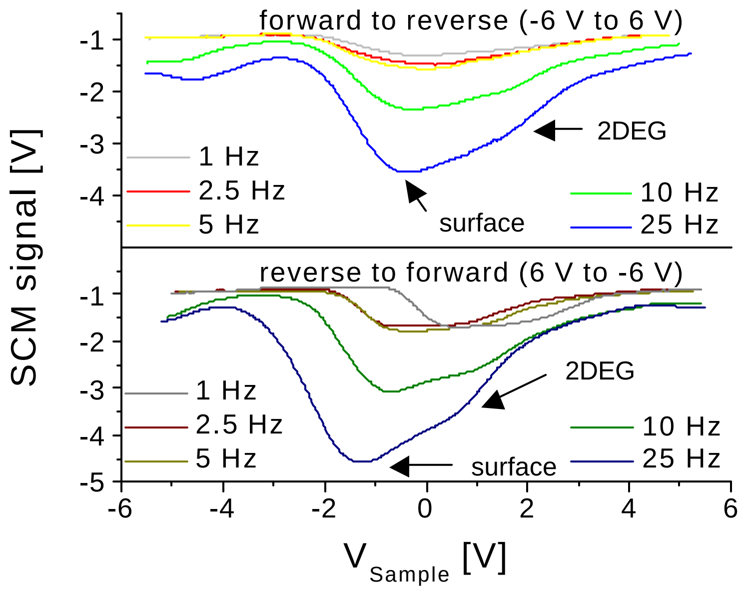


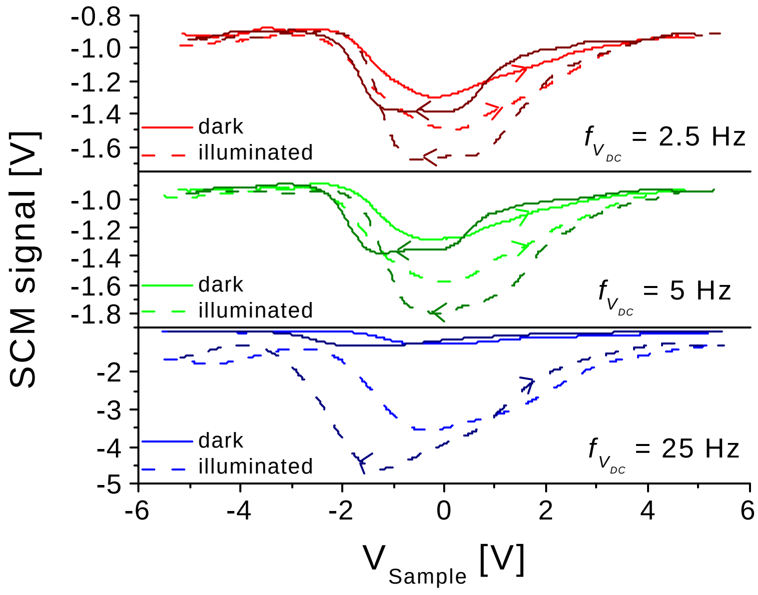
- Bias changed from forward to reverse (f→r):
  - one peak (due to charge in 2DEG)
  - peak position remains nearly constant with increasing ramp frequency
- Bias changed from reverse to forward (r→f):
  - Two peaks ($Al_xGa_{1-x}N$ surface, 2DEG) [K. V. Smith et al., *APL* **75**, 2250 (1999)]
  - Second peak is result of charge being trapped at surface during forward bias (f→r)
  - Peak positions change as f_{VDC} increases

- Hysteresis is observed in *dC/dV* data measured with V_{DC} ramp from -6 V to 6 V (f→r) and from 6 V to -6 V (r→f)
- Hysteresis becomes larger with increasing ramp frequency f_{VDC}

⇒ charge trapping

dC/dV on background location, illuminated





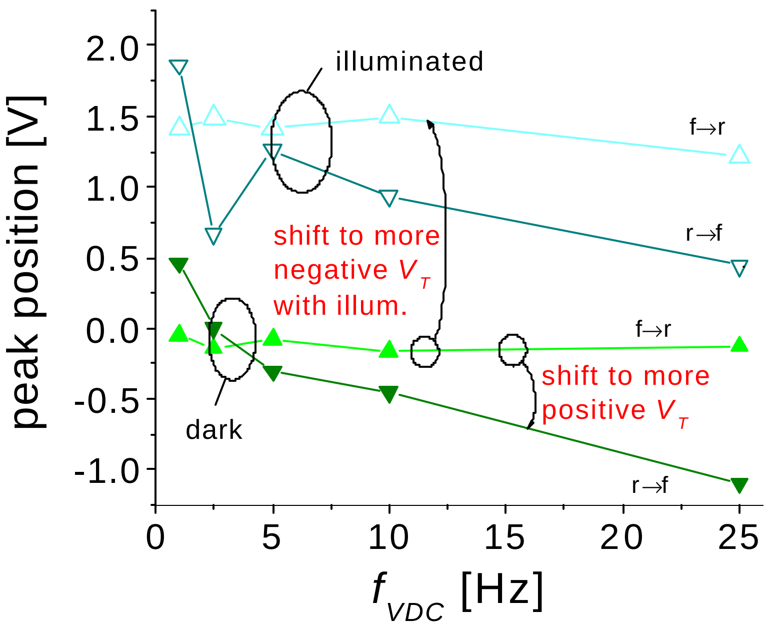
- two peaks (surface, 2DEG)
- Bias changed from forward to reverse (f → r):
  - peak positions stay nearly constant with changes in ramp frequency
- Bias changed form reverse to forward (r → f):
  - Peak positions change with increases

- Hysteresis slightly smaller with illumination

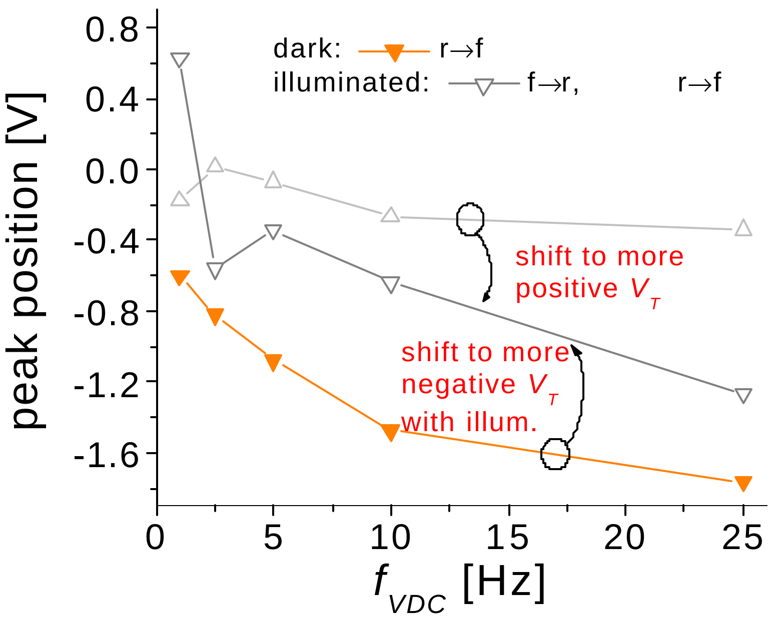
⇒ reduced charge trapping

Background loc.: peak positions as a function of $f_{V_{DC}}$

peak due to 2DEG



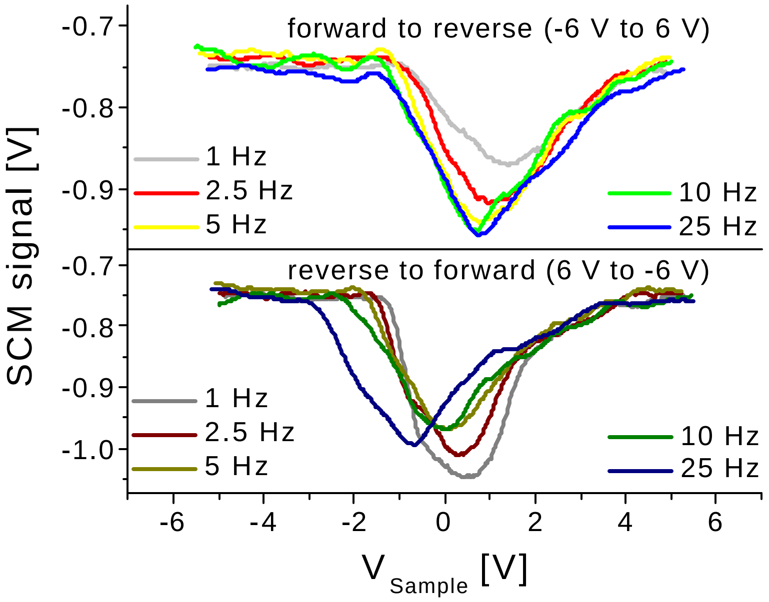
peak due to surface charge



- Peaks shift to more negative values (equivalent to more positive V_T) with change in ramp direction from f→r to r→f
  ⇔ reduction of the electron concentration by traps capturing electrons
- Peaks shifts to more positive values with illumination (equivalent to more negative V_T)
  ⇔ increae in electron concentration due to electron-hole pair generation and reduced electron capturing
- Hysteresis in 2DEG peak between f→r and r→f ramp increases with increasing frequency
  ⇔ trap time constant on the order of several ms

dC/dV near dislocation, dark vs. illuminated

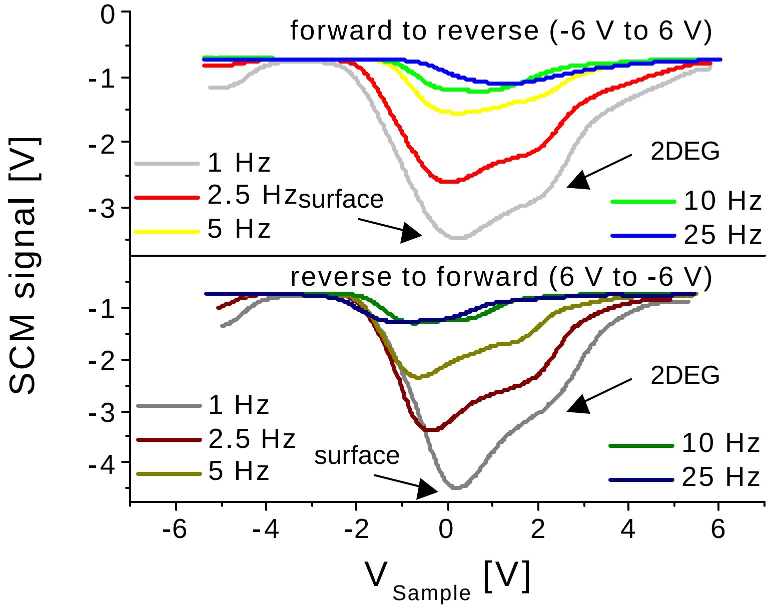
dark



- one peak, does not correspond to surface charge or 2DEG peak
- peak position changes with increasing ramp frequency

⇒ *dC/dV* spectra are different from those on background location

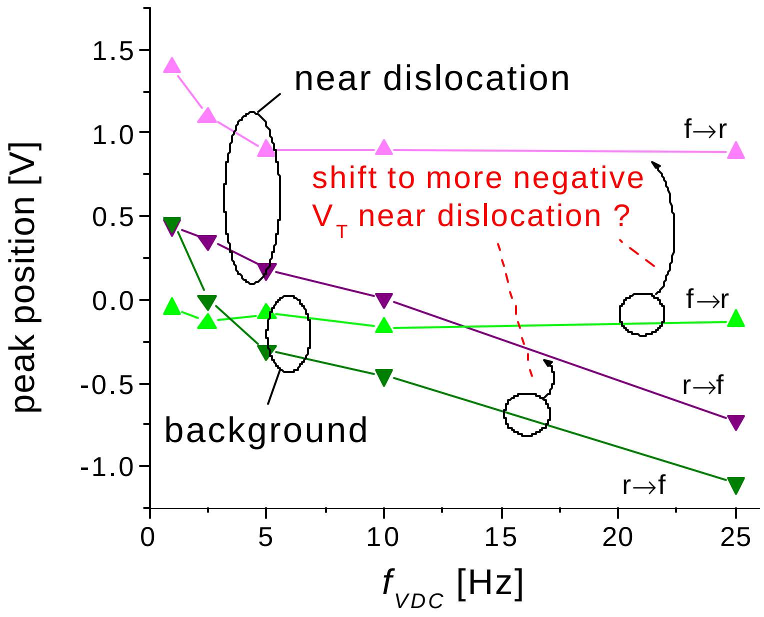
illuminated



- two peaks (surface, 2DEG)
- f → r: peak positions stay nearly constant with changes in ramp frequency
- r → f: peak positions change with increases

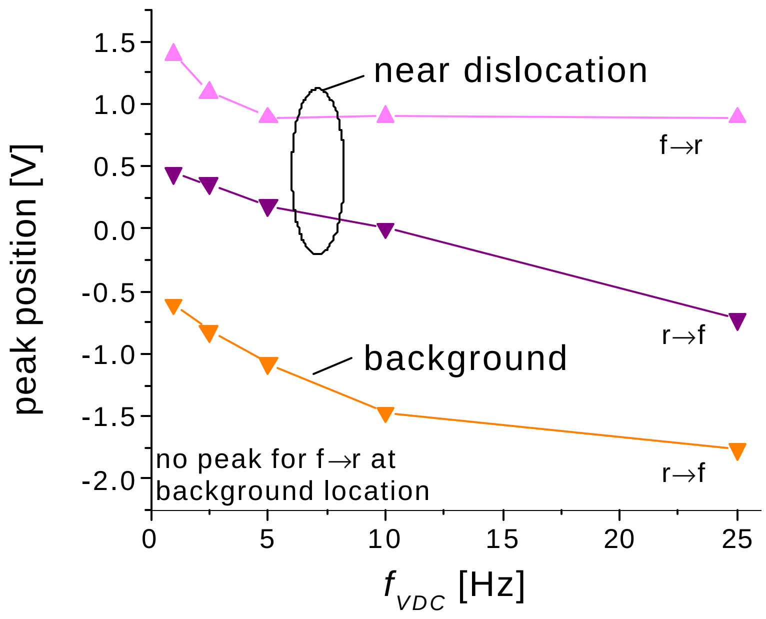
⇒ *dC/dV* spectra are similar from those on background location

Background vs. near dislocation: dark



peak due to 2DEG

shift to more negative V_T near dislocation ?



peak due to surface charge

no peak for f→r at background location

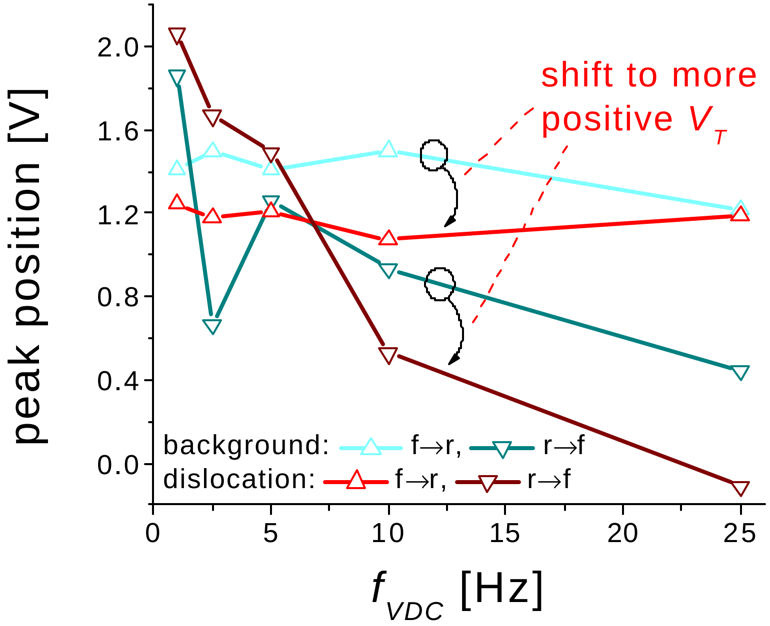
- If shift to more negative V_T ⇒ higher electron concentration in 2DEG?
- Previous measurements have shown that charged threading dislocations cause shift to more positive threshold voltage, i. e. lower carrier concentration

- No modulation of charge in the dark on background location for f→r bias ramp
- Charge is modulation near dislocation for f→r bias ramp

⇒ Single peak does not correspond to 2DEG or surface, probably due to response of traps associated with dislocation

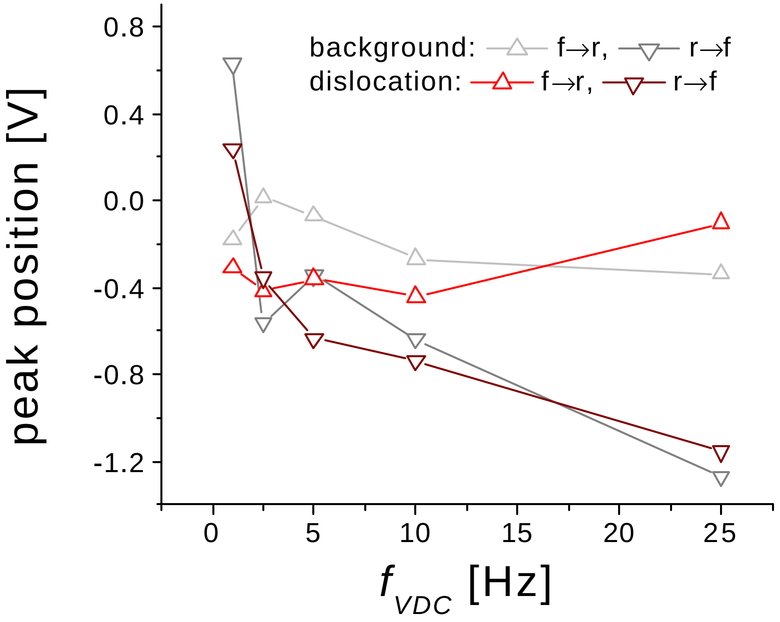
Background vs. near dislocation: illuminated

peak due to 2DEG



- Peaks shift to more negative values (equivalent to more positive V_T) for measurement near dislocation
  - ⇔ reduction of the electron concentration in 2DEG due to potential of charged dislocation [Schaadt et al., *APL* **78**, 88 (2001)]

peak due to surface charge



- virtually no change between measurement on background location and near dislocation
  - influence of electrostatic potential due to charged dislocation small at surface
  - Consistent with ballistic electron emission measurements [H. J. Im et al., *28th PCSI*, Lake Buena Vista, Fl (2001)]

Summary

- SCM used to characterize the frequency-dependent response of surface charges and of charge in the 2DEG of an $Al_xGa_{1-x}N/GaN$ HFET structure.
- *dC*/*dV* spectra were recorded as functions of tip-sample bias voltage with the applied voltage signal consisting of a triangle wave at frequencies of 1 - 50 Hz.
- Spectra were obtained in the dark and in the presence of illumination, both in the space between dislocations (background location) and in the vicinity of a dislocation.
- *dC*/*dV* spectra obtained at the background location:
    - Trapping of electrons 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.
    - Reduced electron capturing is observed in the presence of illumination.
- *dC*/*dV* spectra obtained in the vicinity of a threading dislocation:
    - Shift to more positive V_T in the presence of illumination corresponding to reduction of electron concentration due to additional electrostatic potential of 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.