Bias-Stress Instability in GaN Field-Effect Transistors

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Application space for future power electronics

Important role for GaN power electronics in future
Favored structure: GaN MIS-HEMT

- MIS-HEMT: Metal-Insulator-Semiconductor High Electron Mobility Transistor

- High-mobility 2DEG at AlGaN/GaN interface
- Dielectric to suppress gate leakage current and increase gate swing
- On Si for low cost
Main concern with GaN MIS-HEMTs: reliability and stability

- Si substrate $\rightarrow$ defects in GaN
- Multiple interfaces, many trapping sites
- Uncertain electric field distribution across gate stack
Bias-Temperature Instability (BTI)

Device stability during operation: key concern, particularly $V_T$

- $\text{Al}_2\text{O}_3/\text{AlGaN/GaN}$
- $\text{SiN/AlGaN/GaN}$
- $\text{HfO}_2/\text{AlGaN/GaN}$

Lagger, IEDM 2012
Zhang, SST 2014
Winzer, PSSa 2016
BTI in GaN MOSFETs

Simpler than MIS-HEMTs: single GaN/oxide interface

- Industrial prototype devices
- Gate dielectric: SiO$_2$/Al$_2$O$_3$ (EOT=40 nm)

Guo, IRPS 2015
Guo, IRPS 2016
Guo, TED 2017
Experimental methodology

Constant-$V_{GS}$, stress-interrupt experiments at RT:

1. **Device initialization** through thermal detrapping step
   - Minor impact: $\Delta V_T < 20$ mV, $\Delta S < 30$ mV/dec

2. **Stress and characterization**: measure $V_T$, peak $g_m$, $S$ at $V_{DS}=0.1$ V
   - After 50 characterization runs: $\Delta V_T < 10$ mV, $\Delta g_m < 0.02$ mS/mm, $\Delta S < 15$ mV/dec

3. **Recovery phase** with terminals grounded and periodic characterization

4. **Final thermal detrapping**
Threshold voltage evolution

- PBTI: $V_{GS,\text{stress}}>0 \rightarrow \Delta V_T>0$
- NBTI: $V_{GS,\text{stress}}<0 \rightarrow \Delta V_T<0$
- $|\Delta V_T|$ increases with stress voltage and time
- Fully recoverable $\rightarrow$ no defect generation

Guo, TED 2017
Transconductance evolution

• PBTI: $V_{GS,\text{stress}}>0 \rightarrow g_{m,\text{max}} \downarrow$
• NBTI: $V_{GS,\text{stress}}<0 \rightarrow g_{m,\text{max}} \uparrow$
• $|\Delta g_m|$ increases with stress voltage and time
• Fully recoverable $\rightarrow$ no defect generation

Guo, TED 2017
Subthreshold swing evolution

- **PBTI**: $V_{GS, stress} > 0 \rightarrow S$ unchanged
- **NBTI**: $V_{GS, stress} < 0 \rightarrow S$ unchanged
- No interface state generation
Correlation between $\Delta V_T$ and $\Delta g_m$

- Good correlation between PBTI and NBTI during stress and recovery
- One physical mechanism, fully reversible

Guo, TED 2017
Functional dependence of $V_T$

$V_T$ well described by *power-law function*:

$$\Delta V_T \propto (V_{GS,\text{stress}} - V_{T0})^\gamma t_{\text{stress}}^n$$

Consistent with electron trapping/detrapping in oxide

Guo, TED 2017
PBTI/NBTI: Recoverable electron trapping/detrapping in oxide
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PBTI in HfO₂/InGaAs system

Cai, IEDM 2016
Oxide trapping in other high-k/MOS systems

Al$_2$O$_3$/Si

\[ \Delta V_t (V) \]

\[ 10^{-3} - 10^{-1} \]

\[ 10^{2} \]

\[ 10^{3} - 10^{5} \]

\[ \text{time (sec)} \]

- Zafar, TDMR 2005
- Wu, IEDM 2005
- Franco, IRPS 2014
- Franco, IEDM 2017
Oxide trapping in other high-k/MOS systems

\( \text{Al}_2\text{O}_3/\text{Si} \)

\( \Delta V_f (V) \)

\[ \begin{align*}
\text{time (sec)} &
\end{align*} \]

\( 10^{-3} \)

\( 10^{-2} \)

\( 10^{-1} \)

\( 10 \)

\( 1.5 \text{ V, 140 }^\circ\text{C} \)

\( 2.0 \text{ V, 25 }^\circ\text{C} \)

\( 1.5 \text{ V, 25 }^\circ\text{C} \)

\( 1.0 \text{ V, 25 }^\circ\text{C} \)

\( \text{Zafar, TDMR 2005} \)

\( \text{HfO}_2/\text{Si} \)

\( \Delta V_f (V) \)

\[ \begin{align*}
\text{time (sec)} &
\end{align*} \]

\( 10^{2} \)

\( 10^{3} \)

\( 10^{4} \)

\( 10^{5} \)

\( 10^{6} \)

\( 25 \text{ C} \)

\( \text{Zafar, TDMR 2005} \)
Oxide trapping in other high-k/MOS systems

$\text{Al}_2\text{O}_3/\text{Si}$

$\text{Al}_2\text{O}_3/\text{InGaAs}$

$\text{HfO}_2/\text{Si}$

$\text{HfO}_2/\text{Ge}$

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Franco, IRPS 2014

Franco, IEDM 2017

Wu, IEDM 2005
Oxide trapping in other high-k/MOS systems

- **Al₂O₃/Si**
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Franco, IEDM 2017
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  - Franco, IEDM 2017
What are these defects?

Prime suspect: O vacancies

Formation energy of O vacancies:

Al$_2$O$_3$/GaN band alignment:

Defect states in Al$_2$O$_3$ right above conduction gand edge of GaN

Liu, APL 2010
What are these defects?

Prime suspect: O vacancies

Formation energy of O vacancies:

$$\text{Al}_2\text{O}_3/\text{GaN band alignment:}$$

Defect states smear into bands in amorphous material

Liu, APL 2010
How to mitigate?
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AC BTI more benign
Krishnan, IRPS 2012
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- Introduce SiON interfacial layer
  Cartier, IEDM 2011

- Reduce IG
  Krishnan, IRPS 2012

- Reduce high-k thickness
  Cartier, IEDM 2011

- Short, high-T anneal
  Franco, IRPS 2017

- LaSiO interlayer
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- **Reduce $I_G$**
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NBTI under harsher stress

Guo, IRPS 2016

- Three regimes: Negative $\Delta V_T \rightarrow$ positive $\Delta V_T \rightarrow$ negative $\Delta V_T$
- Permanent negative $\Delta V_T$ after final thermal detrapping
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Trapping in GaN channel under gate edge (recoverable)

Guo, IRPS 2016
NBTF under harsher stress

High-voltage and high-temperature stress:

- Three regimes: Negative $\Delta V_T \rightarrow$ positive $\Delta V_T \rightarrow$ negative $\Delta V_T$
- Permanent negative $\Delta V_T$ after final thermal detrapping
Conclusions

• PBTI and NBTI (benign stress):
  – recoverable $\Delta V_T$, $\Delta g_m$ due to electron trapping/detrapping in pre-existing oxide traps
  – Experimental observations well described by oxide trapping model

• Many avenues for mitigation $\rightarrow$ study Si high-k/MOS literature

• New degradation physics under harsher stress (NBTI):
  – recoverable $\Delta V_T$>0, $\Delta S$ due to electron trapping in substrate
  – non-recoverable $\Delta V_T$<0, $\Delta g_m$, $\Delta S$ due to interface state formation