Plasma-assisted ALD of Silicon Nitride and Gallium Nitride

Harm Knoops
Oxford Instruments Plasma Technology
SiN$_x$ and GaN ALD applications

ALD spacers for transistors

- Oxygen and processing barrier
- Spacing source and drain

Conformal high-quality ALD of SiN$_x$

ALD for GaN HEMTs

- Achieving low defect density at low deposition temperature.
- Potential ALD layers
  - $\text{Al}_2\text{O}_3$
  - $\text{HfAlO}_x$
  - AIN
  - SiN$_x$

ALD of nitrides
Challenges:

- ALD of nitrides often difficult (e.g., low reactivity for thermal processes).
- Desire for robust process and high material quality.

This presentation:

- Recent SiN_x and GaN processes:
  - SiN_x using BTBAS and N_2 plasma
    - Knoops et al., presented at ALD 2013 conference San Diego and ALD 2014 conference in Kyoto
  - GaN using TEGa and H_2/N_2 plasma
    - Sharp et al., poster at ALD 2013 conference San Diego
- Identify important plasma parameters:
  - Pressure, gas mixture, gas residence time.
• Introduction

• ALD of SiN$_x$:
  • Process characteristics
  • Effect of residence time

• ALD of GaN:
  • Process characteristics
  • Effect of H$_2$/N$_2$ ratio and plasma pressure.

• Conclusions
Experimental details

FlexAL at NanoLab@TU/e

### ALD cycle

- **SiH$_2$(NH'Bu)$_2$ (BTBAS)**
  - 150 ms
  - 50 ºC

- **N$_2$ plasma**
  - 10 s
  - 600 W
  - 40 mTorr

- **N$_2$, N$_2^+$, N, etc.**

Turbo pump and load-lock for low moisture background.
Saturation curves

- ALD behavior (soft saturation)
- Growth-per-cycle (GPC) decreases with increasing temperatures.
- GPC shows first fast increase and then a slow decrease to final value.
Linear growth with no growth delay for all temperatures.
- Growth-per-cycle (GPC) decreases with increasing temperatures.
Effect of temperature and plasma exposure

- Decrease of C and H with temperature and plasma exposure
- Films are N-rich but become nearly stoichiometric at 500 °C
- Decreasing plasma pressure to 10 mTorr → less impurities: 6% C, 5% O
Remote plasma
- High radical density at low ion bombardment enabling high material quality → Fast saturation even at low temperatures

Fast pressure control and turbo pump
- Efficient use of precursor and fast saturation
- Quick removal of reaction products even at room temperature
Material properties affected by change of flow and pressure control.

Data from films with different flow, follow residence time trend.
  - Best material properties for short residence time.
Gas residence time:

- **Long**: high GPC due to C from redeposition at short plasma exposures; long plasma exposure to “clean” surface
- **Short**: only small effect from redeposition
• Introduction

• ALD of SiN$_x$:
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  • Effect of residence time

• ALD of GaN:
  • Process characteristics
  • Effect of H$_2$/N$_2$ ratio and plasma pressure.

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FlexAL system

GaN ALD cycle at 300 °C

GaEt₃ (TEGa)
250 ms
30 °C

H₂/N₂ plasma
30:10 sccm
5 s, 300 W
5 mTorr

H₂, N₂, H₂⁺, N₂⁺, H, N, NH₃, etc.
GaN – achieving saturation

- 20:20 H₂/N₂ plasma (G.R.).
  - Slow soft saturation.
- 30:10 H₂/N₂ plasma and APC closed (G.R.*).
  - Faster/normal saturation.
  - Lower GPC of ~0.4 Å/cyc
- Comparison dosing methods:
  - Restricting the flow leads to a shorter half-cycle than in full flow.
  - Increase in precursor consumption efficiency.
• Moving to H₂-rich plasmas increases the refractive index
  • Also drops growth rate – implication of increase in film quality or precursor absorption effect.

• Decreasing the plasma pressure again shows the same trend
  • Previous learning is that lower pressure = higher ion energy = higher film quality
  • Or redeposition effect.
GaN – improving the quality

- 15 mTorr for 5 seconds
  - 15 at% C
  - 10 at% O

- 7 mTorr for 5 seconds
  - 2 at% C
  - 4 at% O

- 7 mTorr for 30 seconds
  - 2 at% C
  - 2 at% O
Effect of temperature

- ALD window found between 150 and 350 °C
- Increase in temperature yields an increase in R.I. up to 2.11 at 300 °C.
Best material obtained so far at:
- 350 °C temperature
- 10 s plasma at 5 mTorr
- H₂/N₂ plasma (30:10)
- 400W power
Conclusions

- ALD of SiN$_x$ using BTBAS and N$_2$ plasma
  - Reduced carbon and hydrogen content with longer plasma exposure or lower pressure.
  - Wide temperature window. Close to Si$_3$N$_4$ for high temperature deposition.
  - Residence time an important “hidden” parameter, due to redeposition effect.

- ALD of GaN using TEGa and H$_2$/N$_2$ plasma
  - Higher quality with higher H$_2$:N$_2$ ratio and low plasma pressure.
  - ALD window between 150 °C and 350 °C
  - Close to GaN composition.