ALD Capabilities at MRC UT Austin

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ALD reactors at MRC – Savannah-100

Savannah-100 Cambridge ALD (2007)

- Precursors – as Nov 2012

0= water 1= trimethyl Al (TMA). RT

2= MgO- amidinate (2-28-10) 3= BeO (Liquid 2-6-12) Pattent 4= tetrakis(dimethylamino) Hf TDMHf. 115C. - 0.97A/cycle

5= ammonia gas

- N2 carrier

ALD reactors at MRC – Savannah-xxx

Savannah Cambridge ALD (2009)

0= water 1= Al – 0.92A/cycle 2= Hf 3= La -150C

Pure La_2O_3 absorbs moisture quickly, so LaAlO is prefered.

4= Zr. 73C - 0.9A/cycle ZrO_2 did not form good interface with III-V. ZrAlO was prefered instead.

5= ammonia

- N_2 carrier

ALD reactors at MRC - Fiji

Fiji ALD Cambridge (2010)

- Precursors:

0= water 1= Al 2= Ti (TDMAT) - 75C

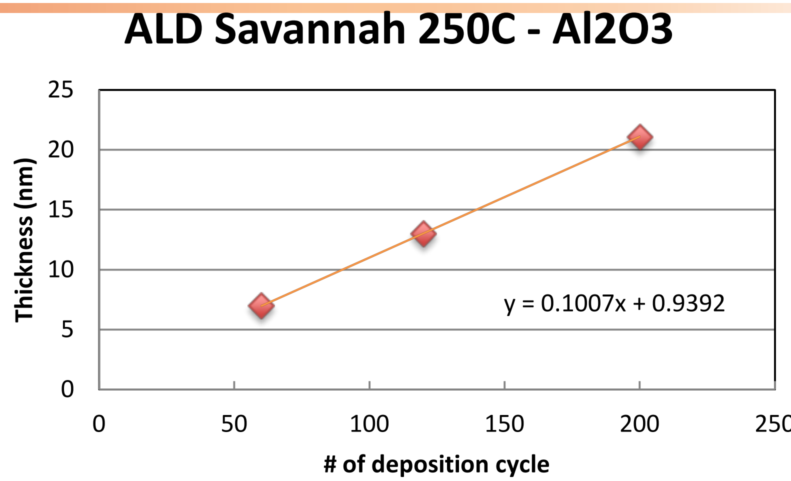
3= Hafnium (TDMHf) -115C

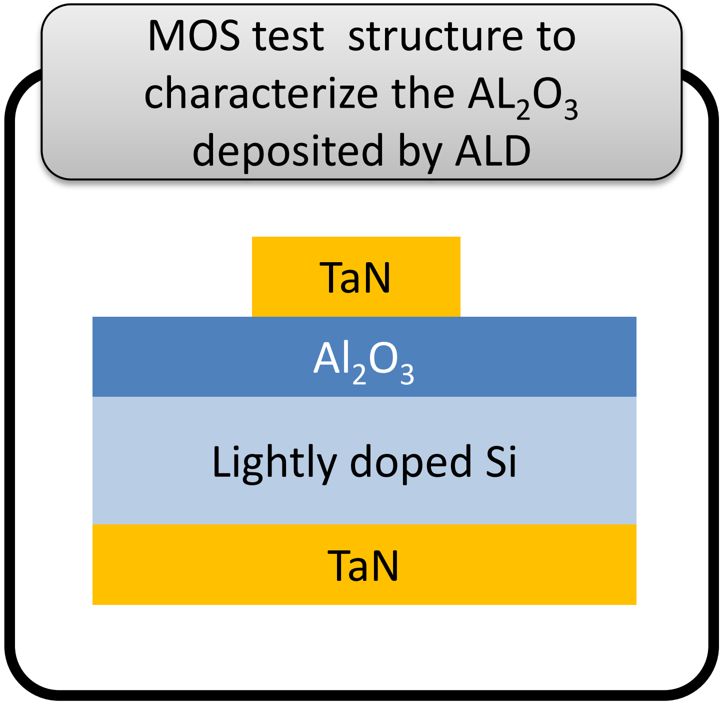
4= Empty. (Set up for low vapor pressure precursor, w/ extra carrier gas input)

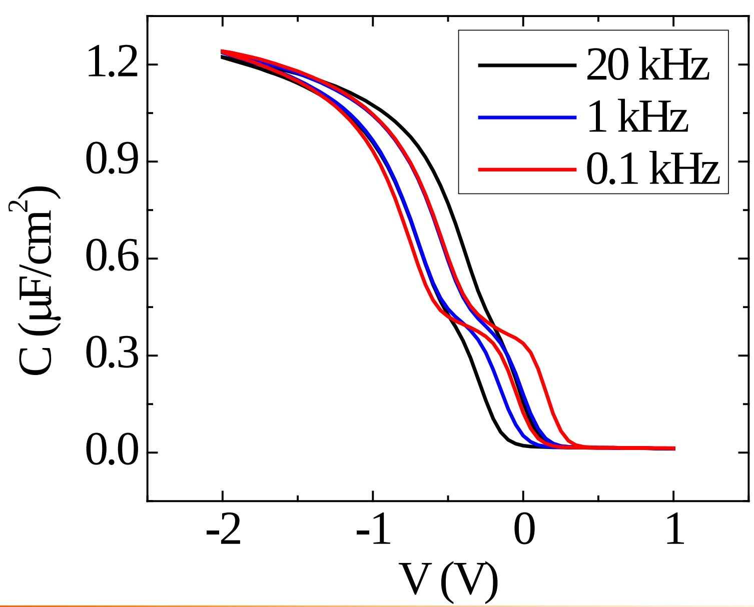
- ICP RF plasma assisted source gases: Ar, N2, H2, NH3, O2
- Ozone generator
- Ar carrier

Al_2O_3 on Si

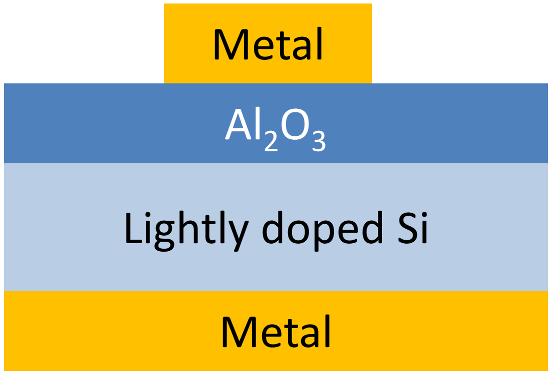
- Precursors : H_2O/TMA
- Chamber temperature: 250/200 °C
- Substrate: lightly doped p-Si (10-20 Ω·cm). HF cleaned

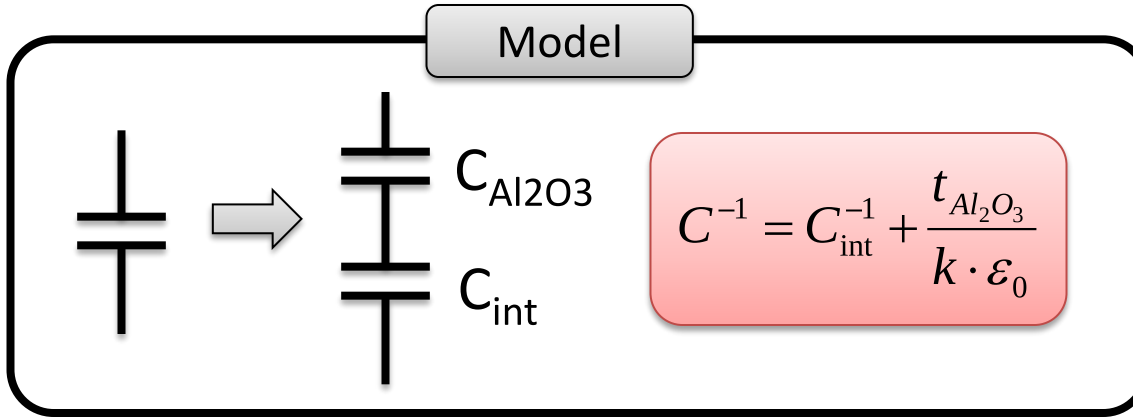


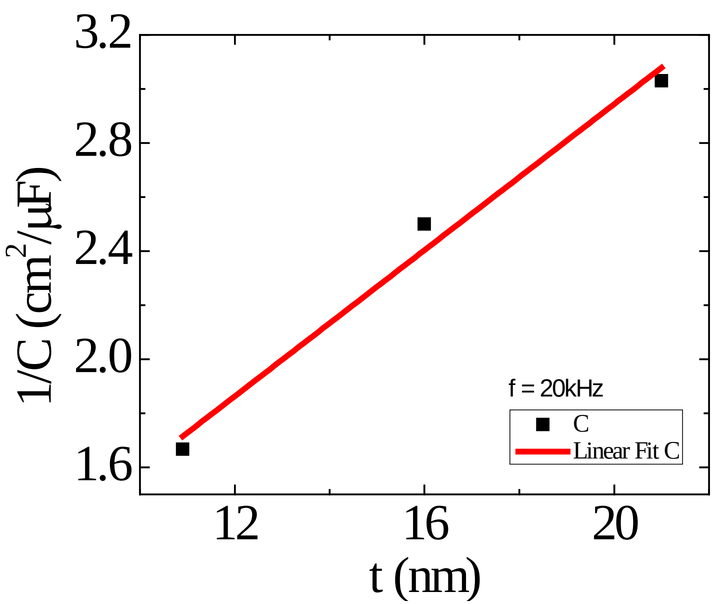




Al_2O_3 on Si: Dielectric Constant (*k*)

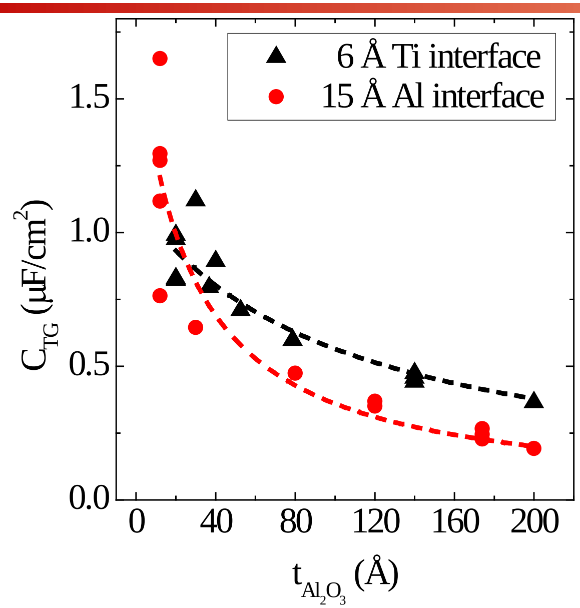


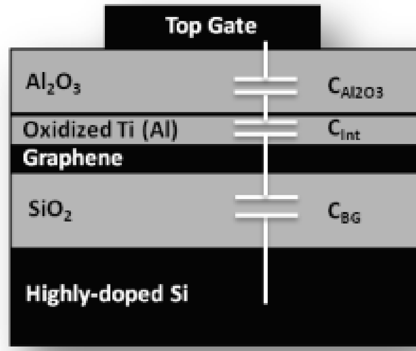




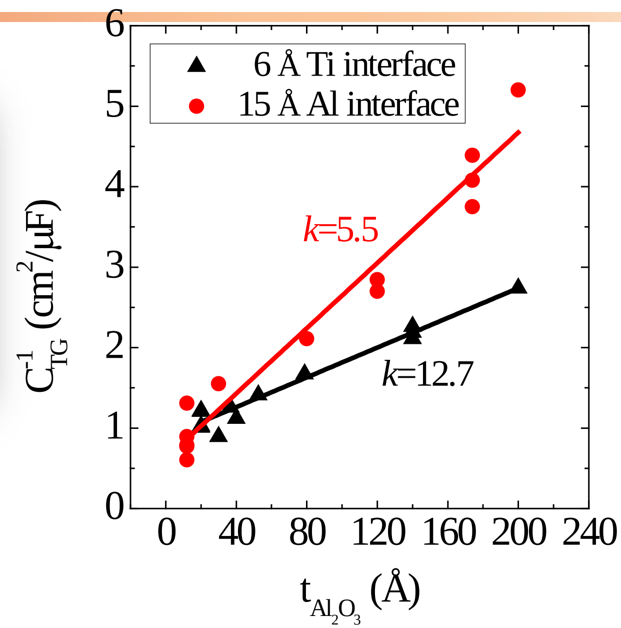
Parameter	Value
Dielectric constant (*k*)	8.4
C_{it} (µF/cm^2)	4.14

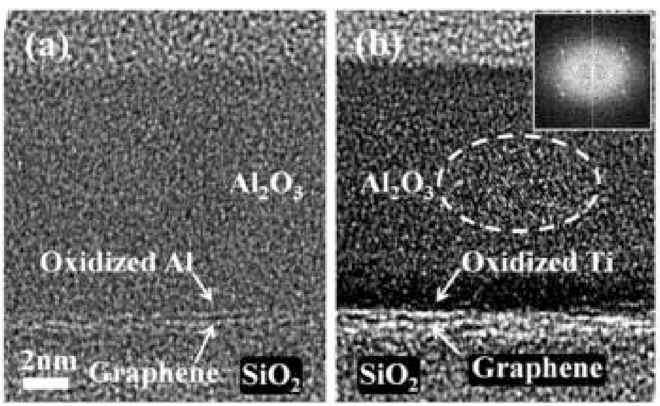
Al_2O_3 on Graphene





$$C_{TG}^{-1} = C_{\text{int}}^{-1} + \frac{t_{Al_2O_3}}{k \cdot \varepsilon_0}$$





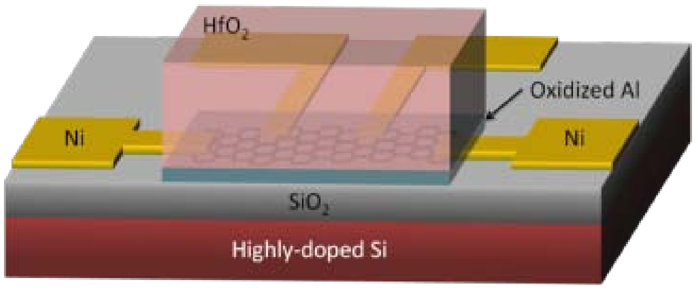
B. Fallahazad *et al,* Appl. Phys. Lett. **100**, 093112 (2012);

- A nucleation layer is required for ALD of dielectrics on graphene
- The nucleation layer has a significant impact on the dielectric constant and morphology of the subsequently grown ALD dielectric

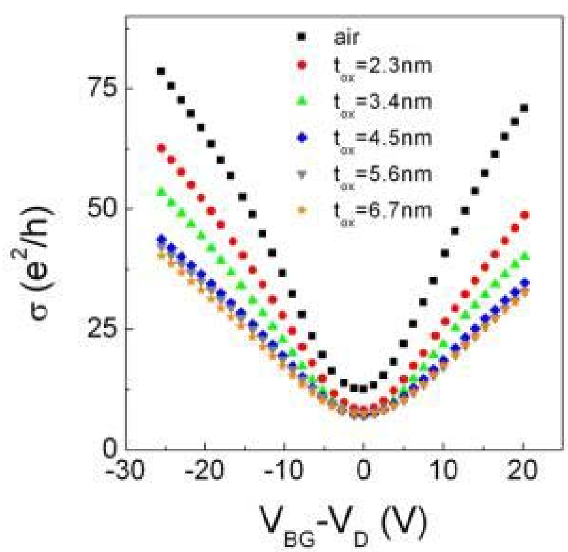
HfO_2 on Graphene

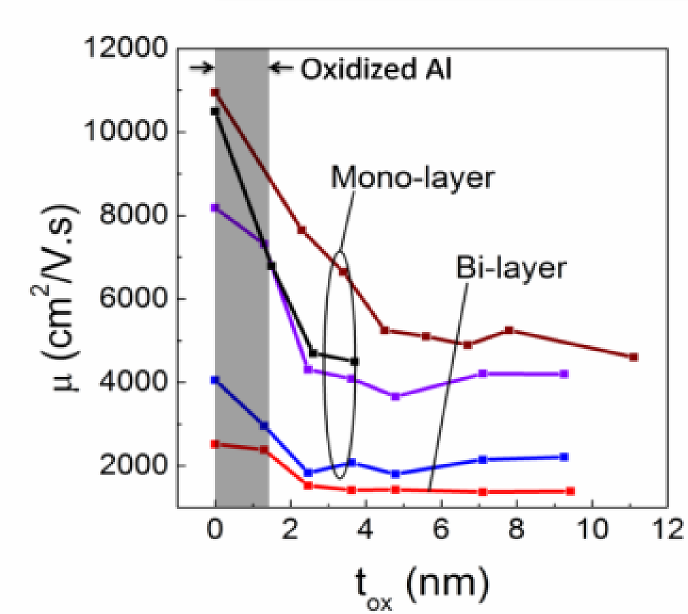
TEMAH: Tetrakis(EthylMethylamino)Hafnium

- Top dielectric stack
  - Interface: Oxidized Al (15Å)
  - Precursor: H_2O/TEMAH
  - Chamber Temperature: 200/200 °C



Dielectric Constant (*k*): 16





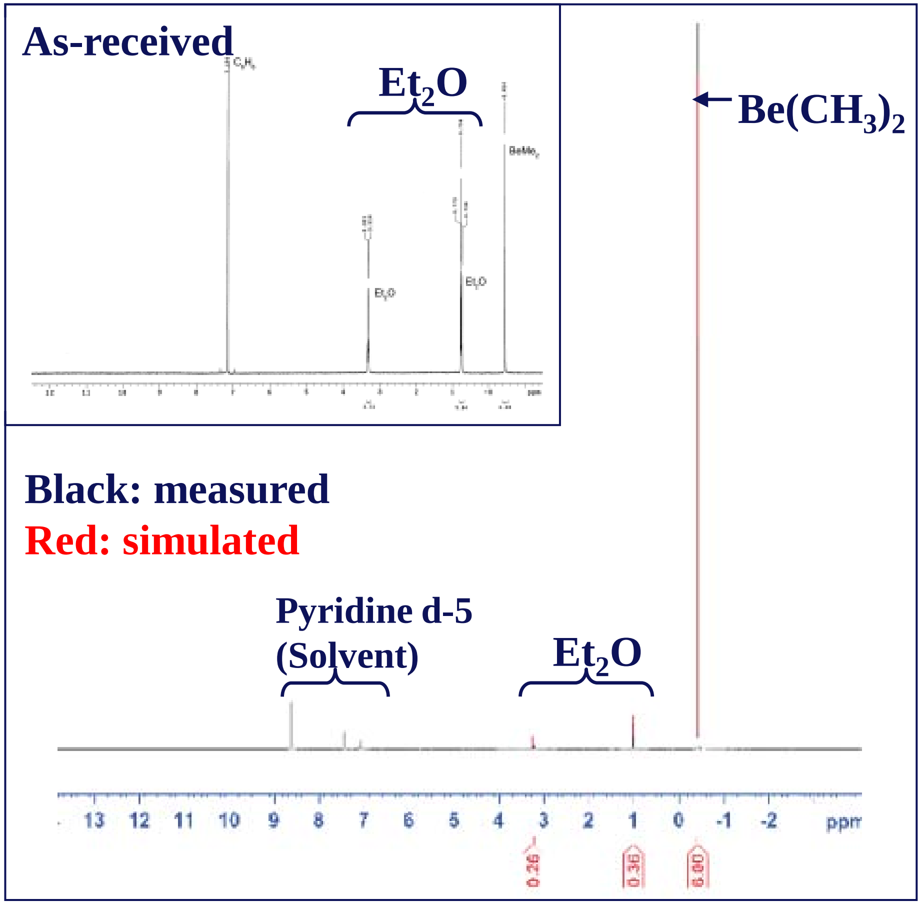
ALD of AlN?

- Precursors: TDMAA/Ammonia
- Temperature: 200-300 C
- Deposition rate: very low (less than 0.1Å /cycle)
- Deposited film very leaky

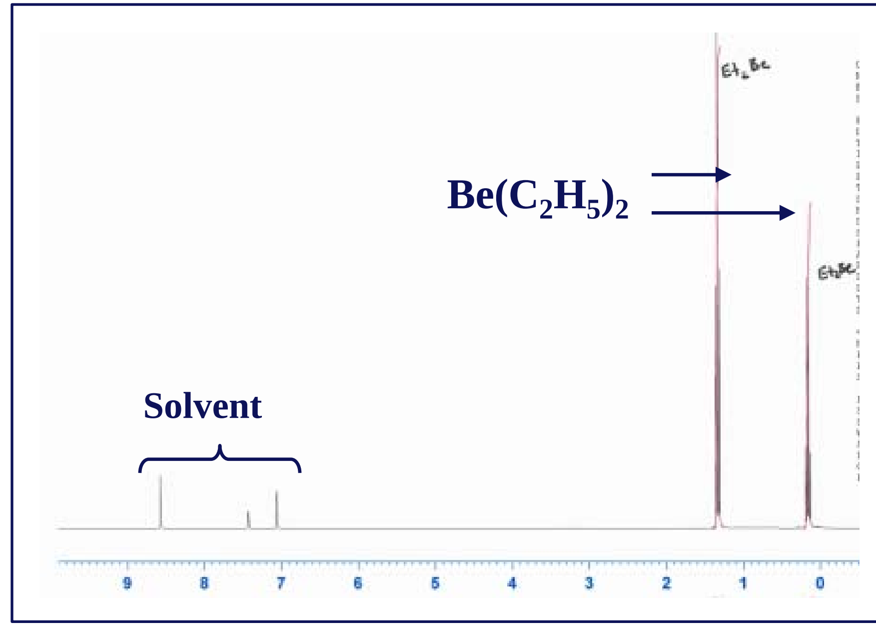
TDMAA: Tris(DimEthylAmido)Aluminum

ALD BeO precursor synthesis

Dimethylberyllium (solid)



Diethylberyllium (liquid)



Grinard metathesis:

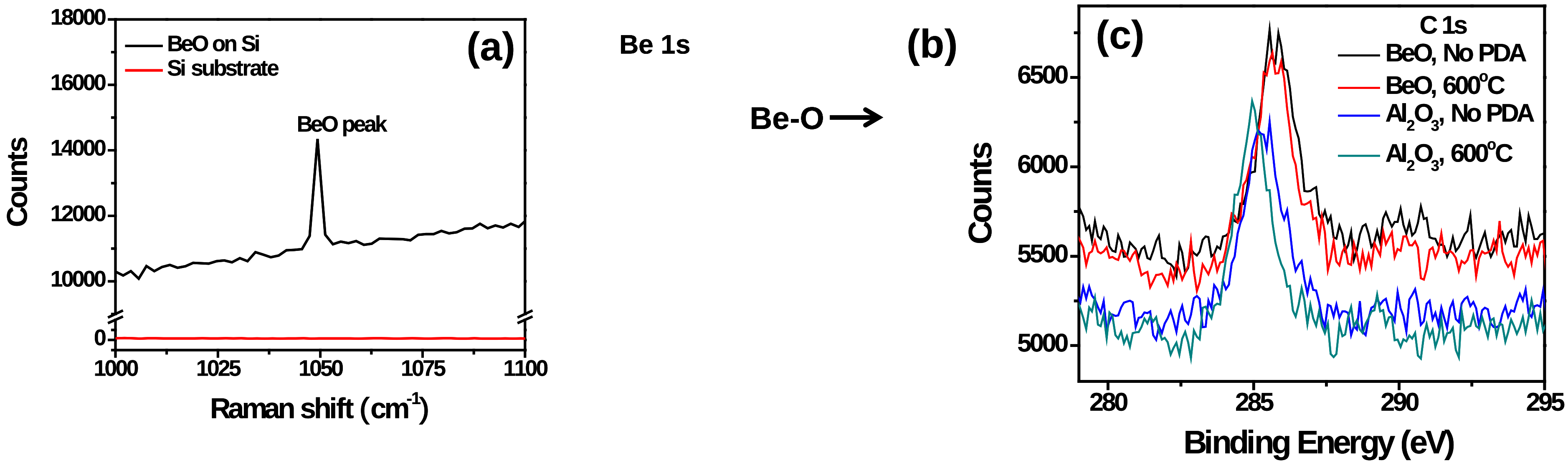
$BeCl_2 + 2CH_3MgBr \rightarrow Be(CH_3)_2 + 2BrCl$

Ether (solvent): $C_2H_5OC_2H_5$

(very stable liquid)

- ❑ **ALD BeO precursors were successfully synthesized.**
- ❑ **After multiple rounds of sublimation, ether impurities were much reduced.**

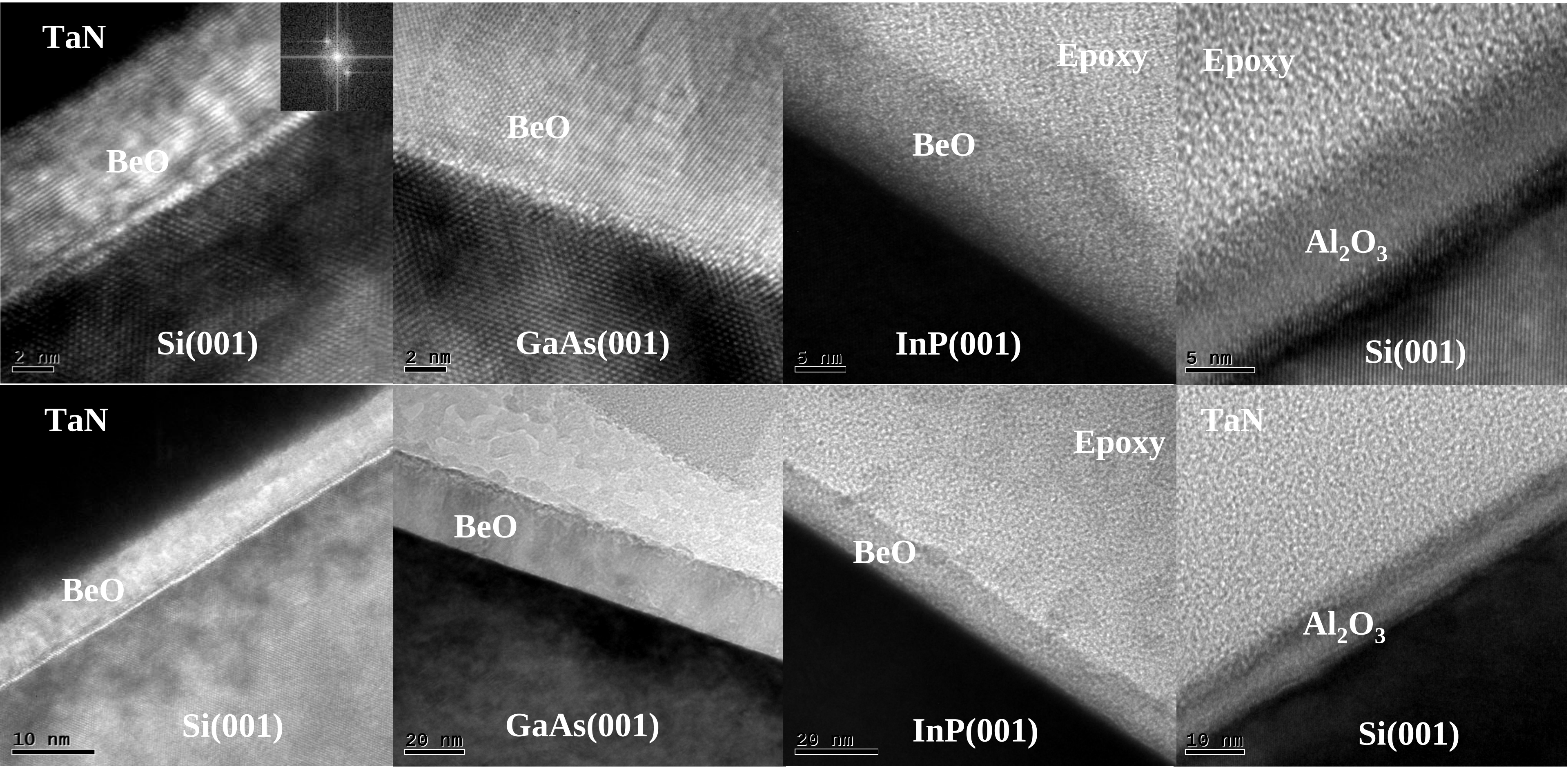
Successful Deposition of ALD BeO



(a) Raman spectrum, (b) XPS of Be 1s, (c) XPS of C 1s.

- ❑ **From Raman and XPS, ALD BeO film is successfully deposited.**
- ❑ **ALD BeO shows slightly higher carbon impurities due to low quality of synthesis.**

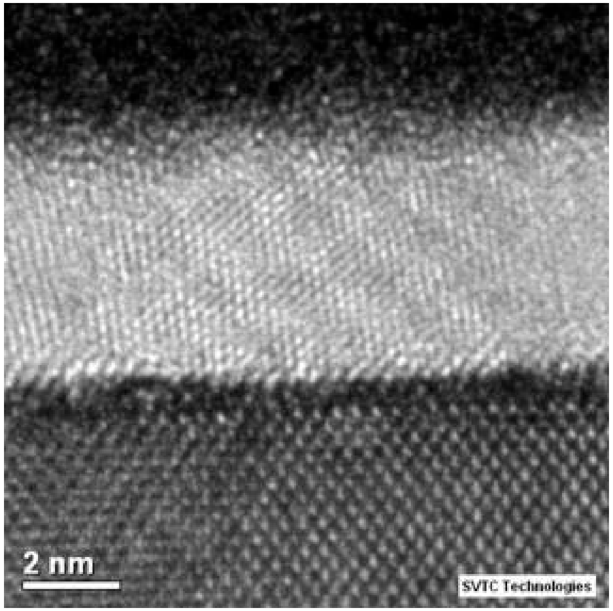
TEM images of ALD BeO Film

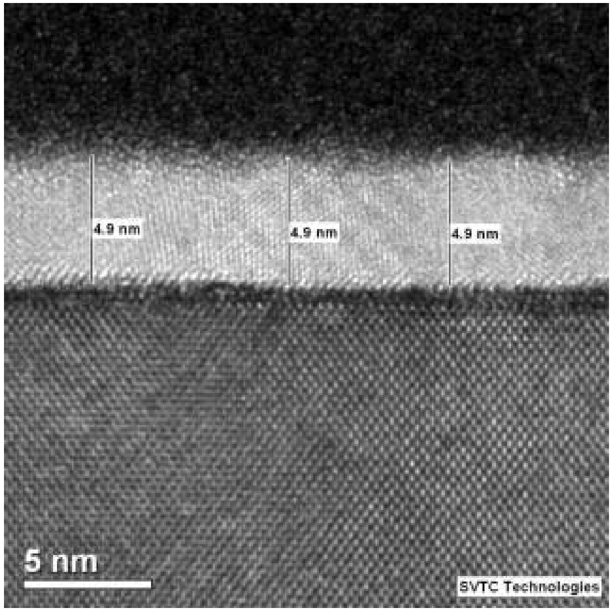


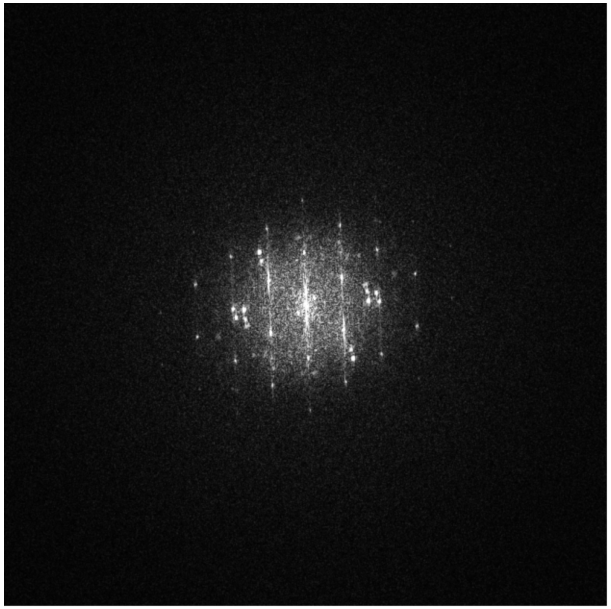
- ❑ **As-grown ALD BeO on Si and GaAs shows high crystallinity.**
- ❑ **ALD BeO shows a relatively distinct interface.**

TEM images of ALD BeO Film

ALD BeO on Ge substrate



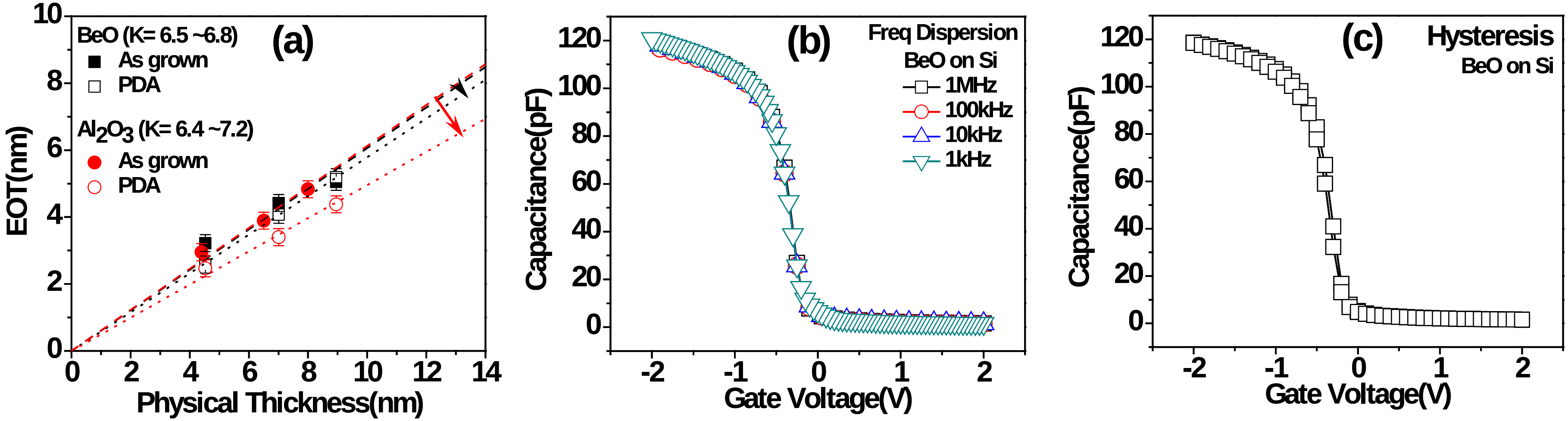




- ❑ **As-grown ALD BeO on Ge shows high crystallinity.**
- ❑ **ALD BeO shows a relatively distinct interface.**

Fundamental electrical analysis for MOS capacitors

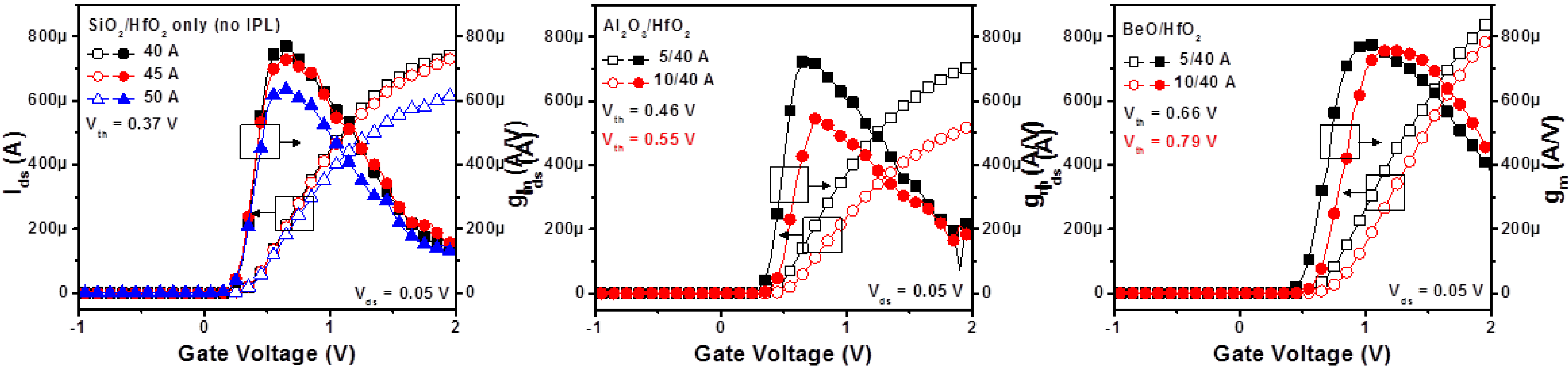
TaN/BeO/p-Si (MOS) structure



(a) Physical thickness versus EOT without/with PDA, (b) Frequency dispersion and (c) Hysteresis.

- ❑ALD BeO shows negligible frequency dispersion and hysteresis.
- ❑The dielectric constants of the BeO film are k = 6.5 before annealing and k = 6.8 after annealing.
- ❑ The Al_2O_3 dielectric constant changes significantly by annealing, from k = 6.4 to 7.2.

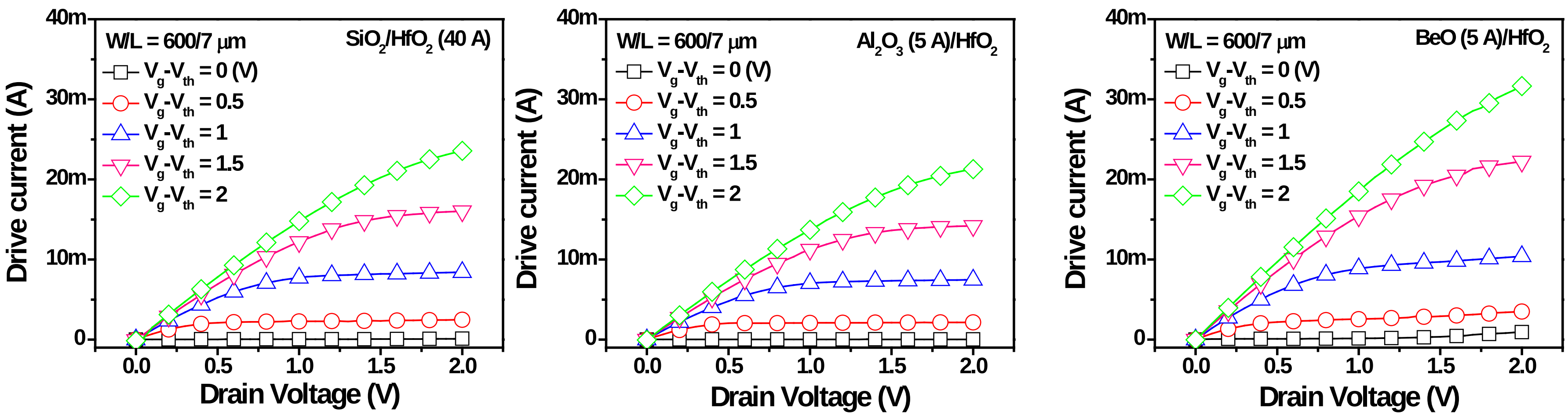
Si MOSFETs characteristics



NMOSFETs I_d-V_g characteristics of SiO_2/HfO_2, Al_2O_3/HfO_2, and BeO/HfO_2 gate stacks.

- ❑ **With the slightly lower EOT, the BeO/HfO_2 stack exhibits more positive V_{th} (0.66 V), higher drive current at Vg = 2 V**
- ❑ **From literature, interface charge (including interface trapped charge and interface fixed charge) is "+" value. So BeO IPL may reduce the interface charge and result in a higher threshold voltage.**

Si MOSFETs characteristics



I_d-V_d characteristics of SiO_2/HfO_2, Al_2O_3/HfO_2 and BeO/HfO_2 gate stacks.

- **BeO/HfO_2 gate stack shows significant increased drive current compared to SiO_2/HfO_2 and Al_2O_3/HfO_2 gate stacks.**

Conclusions

BeO vs Al_2O_3 vs HfO_2

	BeO	Al_2O_3	HfO_2
1.Thermal stability	Better	Middle	Poor
2. E_g & ΔE_c	Larger (10.6eV, 2.3eV)	(8.5eV, <1.9eV)	Lower
3. Diffusion barrier	Better	Middle	Poor
4. Self-cleaning effect	Better	Middle	Poor
5. Structural defects	lower	middle	Larger
6. Orbitals	No filled "P" orbital	"P" orbital	"d" orbital
7. Thermal conductivity	High	Poor	Poor

Energy bandgap↑ → Quantum tunneling current↓ → Defect generation↓
Cation and Anion similar → Stacking fault energy↓ → Intrinsic defects↓
Temperature ↑ → Phonon scattering ↑ → Thermal conductivity ↓
Bonding distance ↓ → Orbital splitting ↑ → Energy bandgap↑(10.6eV)
Bonding distance ↓ → Binding energy ↑→ High melting point