『原子層堆積技術（ALD）による成膜技術』

Super high-dielectric constant AlO_x/TiO_y nanolaminates deposited by the atomic layer deposition technique (for diamond MOSFETs)

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Why diamond?

Property (Relative to Si)	Si	GaAs	SiC	GaN	Diamond
Band gap energy	1	1.3	3	3.1	5
Critical breakdown field	1	1.3	12.3	11.7	33.3
Thermal conductivity	1	0.3	3.1	0.9	13.3
Thermal expansion coefficient	1	1.6	1.6	2.2	0.03
Dielectric constant	1	1.1	0.9	0.8	0.5
Electron mobility	1	5.7	0.7	0.8	3.0
Hole mobility	1	0.7	0.1	0.4	6.3
Saturated carrier velocity	1	1.2	2	2.2	2.7
On-losses decrease (BFOM)	1	13.8	17.0	19.0	187.5
Switching loss decrease (BHFFOM)	1	9.6	105.9	109.5	6986
Power-frequency product (JFOM)	1	2.4	605	662	8083
Thermal limitation (KFOM)	1	0.16	4.6	1.5	30.9

$$JFOM = \left(\frac{E_C v_s}{2\pi}\right)^2$$

E_C: Breakdown field
v_s : Saturation velocity

$$KFOM = \sigma_T \left(\frac{c v_s}{4\pi\varepsilon}\right)^{1/2}$$

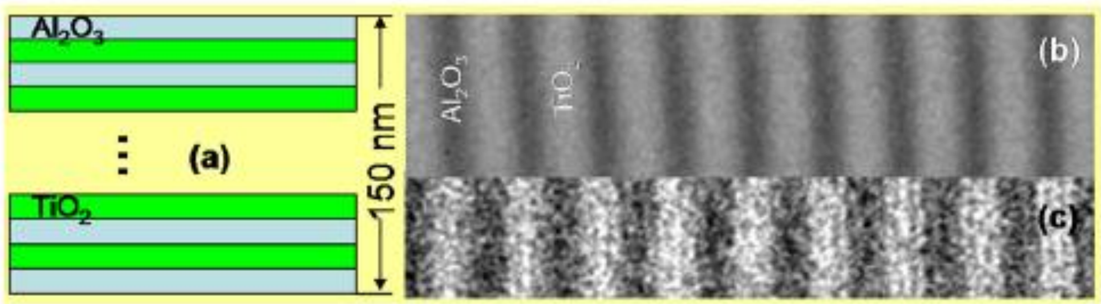
σ_T: Thermal conductivity
c: Light speed
ε: Dielectric constant

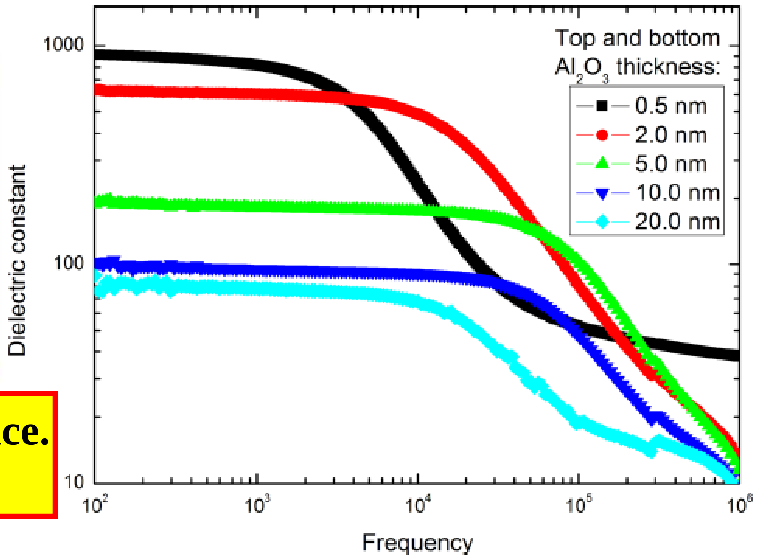
B. J. Baliga, IEEE Electron Dev, Lett. **10**, 455 (1989).

Why AlO_x/TiO_y gate nanolaminate?

k:~1000

Super-high dielectric constant AlO_x/TiO_y nanolaminate





Maxwell-Wagner effect ➔ Charge accumulation at the interface.
Buffer layer is necessary for low leakage current density.

Li, Auciello *et al.*, JAP **110**, 024106 (2011).

AlO_x/TiO_y nanolaminate deposition

Ultratech savannah, USA

Background

Atomic layer deposition equipment for high-*k* materials

2009~now	2012~2021	2018	2021~now

Ensure Nanotech. China
@Tokyo University & NIMS

Picosun Altech, Japan
@NIMS

Ultratech savannah, USA
@University of Texas, Dallas

Samco, Japan
@NIMS

Chemical deposition ➔ Physical pulse/purge process➔ Two precursors

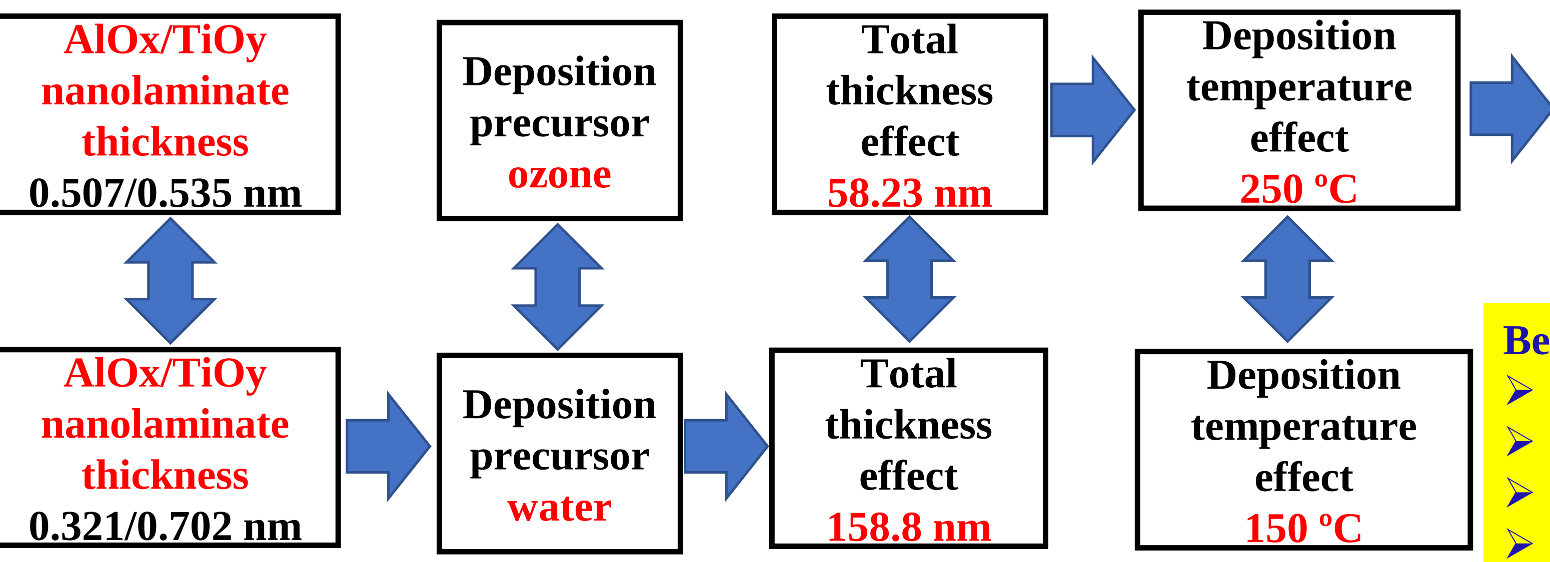
TMA+H_2O $$2Al(CH_3)_3 + 3H_2O \rightarrow Al_2O_3 + 6CH_4$$

TMA+O_3 $$2Al(CH_3)_3 + O_3 \rightarrow Al_2O_3 + 3C_2H_6$$

Merits:
- ✓ Low temperature process
- ✓ Controllable film thickness
- ✓ Corresponding to complex device structures

Metal/AlO_x/TiO_y nanolaminate/metal

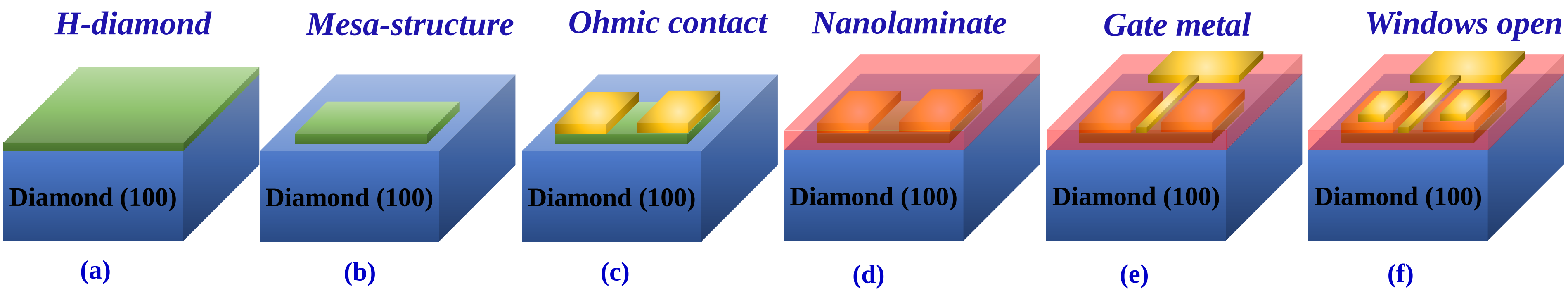
AlO_x/TiO_x Thickness	Precursor	Multilayer Thickness	Buff. Lay. (AlO_x)	Total Th.	Tem.	Leakage current at -2.5 V	C_{max}	*k*
0.507/0.535 nm	water	156.3 nm	5.35 nm	161.7 nm	250 ºC	1.78×10^{-6} A cm^{-2}	0.76 μF cm^{-2}	138
0.321/0.702 nm	water	153.45 nm	5.35 nm	158.8 nm	250 ºC	1.53×10^{-6} A cm^{-2}	1.24 μF cm^{-2}	223
0.321/0.702 nm	ozone	153.45 nm	5.35 nm	158.8 nm	250 ºC	1.38×10^{-3} A cm^{-2}	0.14 μF cm^{-2}	23.6
0.321/0.702 nm	water	52.88 nm	5.35 nm	58.23 nm	250 ºC	2.23×10^{-7} A cm^{-2}	1.69 μF cm^{-2}	111
0.321/0.72 nm	water	52.05 nm	5.35 nm	57.4 nm	150 ºC	2.11×10^{-7} A cm^{-2}	0.83 μF cm^{-2}	53.8



Best conditions:

- AlO_x/TiO_y:0.3/0.7
- Water precursor
- 250 ºC
- Thick film➔*k*
- Thin film➔ *Cmax*

Fabrication of nanolaminate/diamond MOSFETs



MPCVD

Tem.: 900-940 ºC
Press.: 80 Torr
H_2 : 500 sccm
CH_4 : 0.5 sccm
Time: 1.5-2 hrs
Th.: 150-200 nm

CCP-RIE

Tem.: RT
Press.: 10 Torr
O_2 : 100 sccm
Time: 1.5 min
Plasma: 50W

E-gun Evaporator

Press.:10^{-5} Pa
Pd: 10 nm
Ti: 20 nm
Au: 100 nm

ALD

Prec.: TMA, TDMAT, water
Tem.: 250 ºC
0.7nmTiO_y/
0.3nm AlO_x
Total th.: 57.5nm
AlO_x buffer:5 nm

E-gun Evaporator

Press.:10^{-5} Pa
Ti: 10 nm
Au: 150 nm

CCP-RIE

Tem.: RT
Press.: 10 Torr
O_2 : 100 sccm
Plasma: 50W

AlO_x/TiO_y nanolaminate/AlO_x buffer layer/H-diamond MOS capacitor

Liu, *et al. Carbon* **172**, 112 (2021).

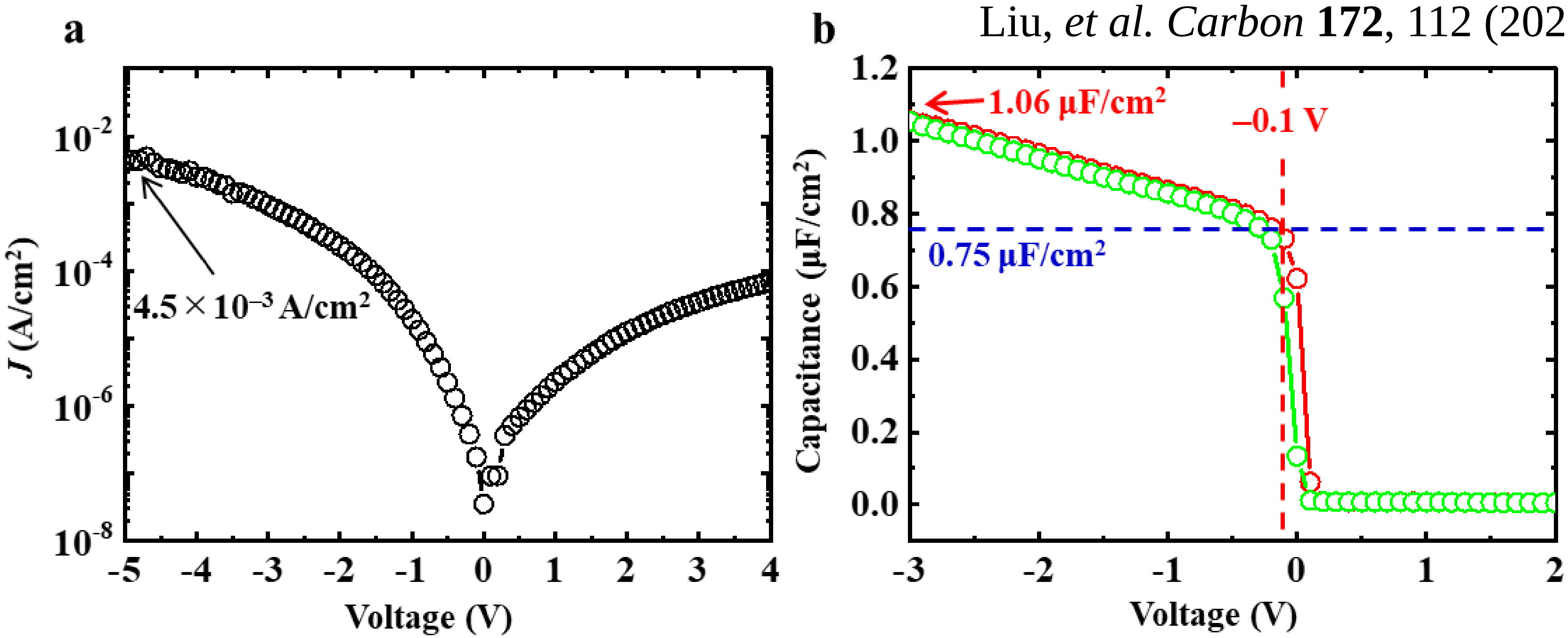


Table 2. Comparation of electrical properties of the AlO_x/TiO_y nanolaminate / H-diamond / H-diamond MOS capacitor with the TiO_y/AlO_x bilayer / H-terminated capacitor.

	d_{AlOx} (nm)	d_{total} (nm)	J (A/cm²)	C_{max} (μF/cm²)	k_{total}	k_{TiOy} $k_{nanolam}$	V_{FB} (V)	V_{hys} (V)
AlO_x/TiO_y nanolaminate	5.0	57.5	4.5×10^{-3}	1.06	68.7	306	–0.1	0.1
TiO_y/AlO_x bilayer	4.0	29.0	1.9×10^{-4}	0.83	27.2	58.0	–1.3	0.06