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Additional Process Information for California Institute of Technology

This document provides additional process information including ALD process of Al_2O_3, HfO_2, SiO_2, TiO_2, AlN, TiN, SiN, GaN and TaN on FlexAl, which were required by the customer. Please notice that all the data in this document are only for reference. The final specification for the Process Acceptance should refer to the data list in the PA file we issued to the customer previously.

Aluminum oxide

Aluminium oxide	Thermal Al_2O_3	Plasma Al_2O_3
Metal precursor	Trimethylaluminum (TMA) CAS: 75-24-1	
Delivery method	Vapour drawn above ambient temperature	
Non-metal precursor **Purge gas**	H_2O Ar	O_2 plasma Ar
ALD temperature window (°C)	120 – 400	25 – 400
Growth per cycle (Å/cycle)	0.95 at 200 °C 1.0 at 300 °C	~1.2 at 200 °C
Thickness uniformity[1] (150 mm) **Run-to-run thickness repeatability[1]**	<± 1.5 % <± 2.0 %	<± 1.5 % <± 2.0 %
Refractive index at 632.8 nm (ex-situ)	1.60 at 120 °C 1.62 at 200 °C 1.64 at 300 °C	1.59 at 25 °C 1.62 at 120 °C 1.64 at 200 °C 1.64 at 300 °C
Breakdown voltage (MV/cm)	>4.0 at 200 °C >4.0 at 300 °C	>7 – 8 at 200 °C >7.0 at 300 °C
Dielectric constant	>5.5 at 200 °C >5.5 at 300 °C	>7 – 8.5 at 200 °C >8.0 at 300°C
Composition	<2 % C, <3 % H at 200 °C	<2 % C, <3 % H at 200 °C
Conformality[2]	>95 % in 20:1 trench	>95 % in 20:1 trench

Notes

[1] See standard definitions of uniformity and repeatability

[2] In some cases to achieve the conformality values extended exposures and purging might be required. Conformality is determined by SEM of trench structure in wafer as film thickness at sidewall (at ¾ of total depth) compared to thickness at the top.

Hafnium oxide

Hafnium dioxide	Thermal HfO_2	Plasma HfO_2
Metal precursor	Tetrakis(dimethylamino)hafnium (TDMAH) CAS: 1996-11-9	
Delivery method	Vapour drawn at 70 °C	
Non-metal precursor	H_2O	O_2 plasma
Purge gas	Ar	Ar
ALD temperature window (°C)	125 – 300	125 – 300
Growth per cycle (Å/cycle)	1.1 at 275 °C	0.7 at 300 °C
Thickness uniformity[1] (150 mm)	<± 3.0 %	<± 2.0 %
Run-to-run thickness repeatability[1]	<± 2.0 %	<± 2.0 %
Refractive index at 632.8 nm[2] (ex-situ)	>2.00 at 200 °C	>2.00 at 200 °C
Breakdown voltage (MV/cm)		>5.0 at 200 °C
Leakage current at 2 MV/cm (A/cm^2)[3]		4.1×10^{-8}

Notes
[1] See standard definitions of uniformity and repeatability
[2] For film thickness >10 nm
[3] For a 250 µm area

Titanium nitride	Plasma TiN
Metal precursor(s)	Tetrakis(dimethylamido)titanium (TDMAT) CAS: 3275-24-9
Delivery method **Bubbler gas**	Bubbled at 70 °C Ar
Non-metal precursor **Purge gas**	N_2/H_2 plasma Ar
ALD temperature window (°C)	100 – 350
Growth per cycle (Å/cycle)[1]	0.5 at 200 °C 1.0 at 300 °C 1.1 at 350 °C
Thickness uniformity[2] (150 mm) **Run-to-run thickness repeatability[2]**	<± 2.5 % <± 2.0 %
Refractive index at 632.8 nm (ex-situ)	>1.45 at 350 °C
Resistivity (µΩcm)[3]	<300 at >200 °C
Composition	

Notes

[1] Growth rates of >1 Å/cycle are achieved for >300 °C deposition temperature impying process is beyond ALD window. Thickness and resistivity remain uniform.

[2] See standard definitions of uniformity and repeatability

[3] For film thickness >40 nm

Silicon dioxide	Plasma SiO_2
Si precursor	Bis(tert-butylamino)silane (BTBAS) CAS: 186598-40-3
Delivery method	Vapour drawn at 35 °C
Non-metal precursor	O_2 plasma
Purge gas	Ar
ALD temperature window (°C)	50 – 400
Growth per cycle (Å/cycle)	1.2 at 300 °C
Thickness uniformity[1] (150 mm)	<± 3.0 %
Run-to-run thickness repeatability[1]	<± 2.0 %
Refractive index at 632.8 nm (ex-situ)	1.42 – 1.46 1.43 at 300 °C
Stress[2] (MPa)	+36
Composition	<5 % C at 300 °C

Notes
[1] See standard definitions of uniformity and repeatability
[2] For film thickness of 300 nm on 100 mm Si (100) wafer

Titanium dioxide

Titanium dioxide	Thermal TiO_2	Plasma TiO_2
Metal precursor	Tetrakis(dimethylamido)titanium (TDMAT) CAS: 3275-24-9	
Delivery method **Bubbler gas**	Bubbled at 70 °C Ar	
Non-metal precursor **Purge gas**	H_2O Ar	O_2 plasma Ar
ALD temperature window (°C)	200 – 350	25 – 300
Growth per cycle (Å/cycle)	0.4 at 200 °C	0.3 at 250 °C
Thickness uniformity[1] (150 mm) **Run-to-run thickness repeatability[1]**	<± 2.0 %	<± 2.0 % <± 2.0 %
Refractive index at 632.8 nm (ex-situ)	2.20 at 200 °C	2.30 at 200 °C

Notes

[1] See standard definitions of uniformity and repeatability

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Silicon nitride

Silicon nitride	Plasma Si_3N_4
Metal precursor(s)	Bis(tert-butylamino)silane (BTBAS) CAS: 186598-40-3
Delivery method	
Non-metal precursor	N_2 plasma
Purge gas	Ar
ALD temperature window (°C)	200 – 400
Growth per cycle (Å/cycle)	0.24 at 200 °C 0.20 at 300 °C 0.20 at 350 °C
Thickness uniformity[1] (150 mm)	<± 3.5 %
Run-to-run thickness repeatability[1]	<± 2.0 %
Refractive index at 632.8 nm (ex-situ)	>1.80 at 100 °C >1.90 at 200 °C 1.90 at 300 °C 1.93 at 350 °C >1.95 at 400 °C
Composition[2]	Si:N ratio: 1:1.4 at 400 °C

Notes

[1] See standard definitions of uniformity and repeatability

[2] Knoops, H. C. M., Braeken, E. M. J., de Peuter, K., Potts, S. E., Haukka, S., Pore, V., Kessels, W. M. M. ACS Appl. Mater. Interfaces, 7(35) (2015) pp 19857-19862

Gallium nitride	Plasma GaN
Metal precursor	Triethylgallium (TEG) CAS: 1115-99-7
Delivery method	Vapour drawn at 30 °C
Non-metal precursor	N_2/H_2 plasma
Purge gas	Ar
ALD temperature window (°C)	150 – 350
Growth per cycle (Å/cycle)	0.4 at 300 °C
Thickness uniformity[1] (150 mm)	<± 3.0 %
Run-to-run thickness repeatability[1]	<± 2.0 %
Refractive index at 632.8 nm (ex-situ)	2.10 – 2.25 at 350 °C

Notes
[1] See standard definitions of uniformity and repeatability

Aluminum nitride

Aluminum nitride	Plasma AlN
Metal precursor(s)	Trimethylaluminum (TMA) CAS: 75-24-1
Delivery method	Vapour drawn above ambient temperature
Non-metal precursor	N_2 plasma
Purge gas	Ar
ALD temperature window (°C)	300 – 400
Growth per cycle (Å/cycle)[1]	0.8 at 350 °C
Thickness uniformity[2] (150 mm)	<± 2.5 %
Run-to-run thickness repeatability[2]	<± 2.0 %
Refractive index at 632.8 nm (ex-situ)	1.95 at 350 °C

Tantalum nitride	Plasma TaN
Metal precursor	Tris(diethylamido)(tert-butylimido)tantalum (TBTDMT) CAS: 169896-41-7
Delivery method **Bubbler gas**	Bubbled at 60 °C Ar
Non-metal precursor **Purge gas**	H_2 plasma Ar
ALD temperature window (°C)	250 – 350
Growth per cycle (Å/cycle)	0.40 at 300 °C
Thickness uniformity[1] (150 mm) **Run-to-run thickness repeatability[1]**	<± 3.0 % <± 2.0 %
Resistivity[2] (µΩcm)	<500 – 5000 at 350 °C
Composition	<5 % C at 350 °C

Notes

[1] See standard definitions of uniformity and repeatability

[2] For film thickness > 40 nm. Resistivity increases with decreasing deposition temperature and film thickness. Turbo pump is essential to achieve low resistivity.

To achieve low resistivity TaN_x films, it is recommended that the FlexAL system is configured with a RF biased electrode. Resistivity of <300 µΩcm (centre point measurement) has been achieved when TaN_x is deposited using TBTDMT/H_2 plasma with the electrode RF biased.

ALD AlN (Plasma ALD)

PARAMETER	METROLOGY	OIPT DATA
Density	XRR	3.26 g/cm^3
Al:N ratio	XPS	1:1.3 Al:N
Carbon and impurity content	XPS	5 at.% C. 5 at.% O.
Time per cycle		12-40 s cycle time

ALD SiN (Plasma ALD)

PARAMETER	METROLOGY	OIPT DATA
Density	XRR	2.97 g/cm^3 (OIPT). 2.8-2.9 g/cm^3 for deposition at 300-500 °C (Knoops *et al*., DOI: 10.1021/acsami.5b06833)
Si:N ratio	XPS	1:1.4 Si:N at 400 °C (Knoops *et al*., DOI: 10.1021/acsami.5b06833).
Carbon and impurity content	XPS	2 at.% C. 4 at.% O at 400 °C PEALD (Knoops *et al*., Appl. Phys. Lett. 107, 014102 (2015)).
Deposition rate	Ellipsometry	0.2 Å/cycle at 350 °C.
Time per cycle		22 s per cycle

ALD GaN (Plasma ALD)

PARAMETER	METROLOGY	OIPT DATA
Refractive Index*	Ellipsometry	2.1 at 350 °C (OIPT)
Density	XRR	5.98 g/cm^3 at 350 °C (OIPT)
Carbon and impurity content	XPS	0.3 at.% C, 1.0 at.% O (OIPT). 2 at.% C and 2 at.% O in bulk GaN film (T. Sharp *et al*., presented at ALD 2013 Conference).
Deposition rate	Ellipsometry	0.4 Å/cycle
Time per cycle		Cycle time: 21 s