Correlations between surface morphology, local thermal and electrical properties of metal oxide thin films studied by scanning probe microscopies

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Motivation

Zinc oxide (ZnO) represents a wide band-gap (3.37 eV), natively n-type, polar semiconductor non-toxic compounds. Alloying ZnO with magnesium oxide (MgO) increases the band-gap of ZnMgO compound from 3.4 eV up to 4.5 eV. The Mg dopind increases the bandgap up to 4.0 eV whilst maintaining the wurtzite structure (to about 40 % of Mg), thus giving access to the deep ultraviolet regions.

Aims

- Determination of local thermal properties of metal oxide thin films deposited on different substrates
- Correlation between thermal and electrical properties and surface morphology

Experiment

Two sets of samples:

- ZnO and Al doped ZnO thin films deposited by ALD on the Si substrates. Thickness of layers: 15 nm, 38 nm, 110 nm, 118 nm.
- ZnMgO thin films deposited by MBE on Si, R- and m-type sapphire substrates. Thickness of layers: ~400 nm

Methods

Scanning Probe Microscopy (XE-70 PSIA Inc.):		
Topography (AFM)	Local thermal (SThM)	Electrical (SKPM)
Probes:		
BS Tap300Al (Budget Sensors)	KNT-SThM-1an Kelvin Nanotechnology	ElectricTap300-G (Budget Sensors) and EFM (Nano World)

AFM imaging

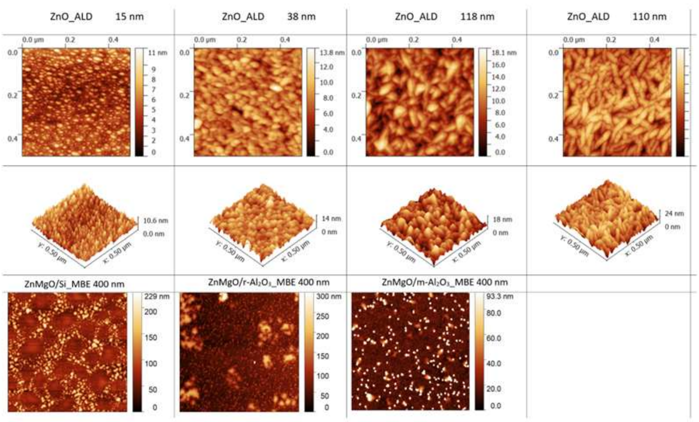

Fig. 1 NC-AFM 1 x 1 μm² topography images of ZnO-ALD samples and 15 x 15 μm² topography images of ZnMgO-MBE samples.

Nano-IR imaging

Amplitude and Phase contrasts of highly doped nanoparticles depend on the free carriers concentration and illumination wavelength. Promising contrast in phase images observed for m-plane Al_2O_3 sample, nano-IR imaging was performed for two wavelenghts: 910 cm^{-1} and 1200 cm^{-1}.

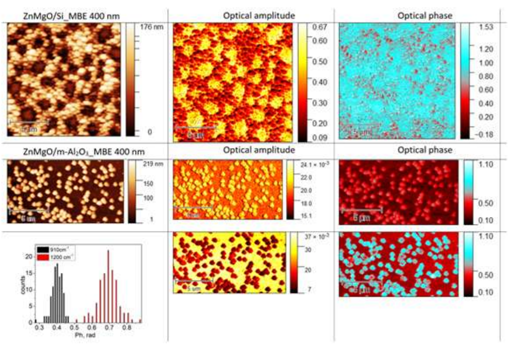

Fig. 2. Nano-IR imaging of thin films: ZnMgO/Si (a, b, c), ZnMgO/m-plane Al_2O_3 (d, e, f, g, h).

SKPM imaging

Areas with formed grains significantly higher contact potential difference (CPD) signal value, compared to the remaining surface of the layer.
The ΔCPD_{grain} estimated as the difference between the CPD signal level on the grain and the signal level recorded on the surface of the layer surrounding the grain.
The grain structures appearing on the surface of the ZnMgO/Si layer characterized by the highest deviation of the CPD signal value compared to the remaining surface of the layer - this is the most heterogeneous layer in terms of the CPD surface distribution.
ZnMgO/R-Al_2O_3 is the layer with the most uniform distribution of surface electronic properties.

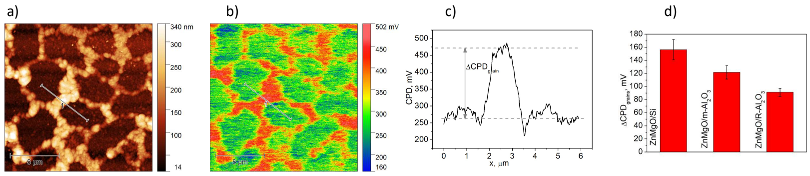

Fig. 2 SKPM 15 x 15 μm² topography images of the ZnMgO/Si recorded on the layer surface a), corresponding CPD surface distributions b), CPD profile recorded along the line across the grain c), and averaged ΔCPD_{grain} values calculated for all investigated samples d).

SThM measurements

$$\frac{(R_d - R_s)_{in}}{(R_d - R_s)_{out}} = \frac{R_{th}|_{in}}{R_{th}|_{out}}$$

$$R_{th}^{-1} = h + \left(R_{thP} + \frac{1}{4\kappa r}\right)^{-1}$$

Where:
h - the effective heat transfer coefficient (convective cooling of the probe),
R_{thP} - the probe thermal resistance,
κ - the thermal conductivity of the sample,
r - the probe-sample contact radius.

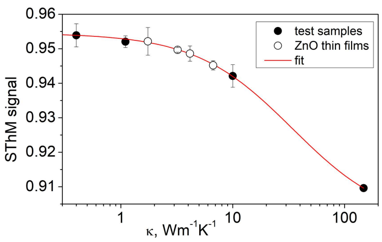

Table 1. Morphological and thermal properties of ZnO samples.

Sample ALD	ZnO	ZnO	ZnO	ZnO:Al
Ra, nm	1.1	1.5	2.4	2.6
d, nm	15	38	118	110
k, W/mK	0.3	1.1	2.8	4.3

Table 2. Morphological, thermal and electrical properties of ZnMgO samples.

Sample MBE	ZnMgO/ Si	ZnMgO/ m-Al_2O_3	ZnMgO/ R-Al_2O_3
Ra, nm	6.3	3.2	8.4
d, nm	400	300	400
k, W/mK	11.0	6.1	12.3
ΔCPD, V	66	16	60

Conclusions

- The SThM technique is used to determine the thermal conductivity of thin dielectric films with resolution better than 100 nm.
- The modified method applied a small ac voltage component to modulate the probe current, a lock-in detection increased sensitivity, but correction procedure is needed in case of ultra thin layers.
- Microscopic investigations showed that type of substrate influenced the surface morphology properties, grain size, grains distribution, islands formation in ZnMgO thin films
- Analysis of ΔCPD signal allowed to conclude that ZnMgO/R-Al_2O_3 is the layer with the most uniform distribution of surface electronic properties.
- The thermal conductivity of ZnO and ZnMgO thin films was correlated with surface morphology, smaller grains – lower k value.

Acknowledgements

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