2011 International Conference on Frontiers of Characterization and Metrology for Nanoelectronics, France

WE-03: Current Voltage Characteristics through Grains and Grain Boundaries of High-k Dielectric Thin Films Measured by Tunneling Atomic Force Microscopy

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Motivation

In our previous study[1]

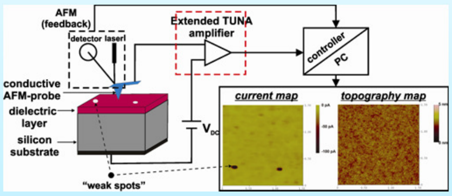
- high leakage current paths through high-k dielectric films ($HfSi_xO_y$ and ZrO_2) were found to be located at the grain boundaries by tunneling atomic force microscopy (TUNA)
- Possible reasons for the larger leakage current through grain boundaries:
  - Different current conduction mechanisms for grains and grain boundaries.
  - Smaller thickness of grain boundaries compared to that of grains.

Purpose of this paper

- Measurements for local *I-V* curves at grains and grain boundaries of high-k dielectric films by TUNA in order to clarify the current conduction difference between the grains and grain boundaries of high-k dielectric films

[1]V. Yanev, *et al.*, *Appl. Phys. Lett.* **92**, 252910 (2008).

TUNA principle



- Atomic Force Microscope (AFM) with a conductive probe operated in contact mode, probe tip acts as top electrode of a MIS structure
- DC bias voltage (V) is applied between tip and sample
- Leakage (tunneling) current through the dielectric layer is measured in dependence on V
- Extended TUNA amplifier (extremely sensitive to low currents): measurable current range: 40 fA to 12.3 pA (in the used sensitivity (1pA/V))

Experimental

Sample preparation

$HfSi_xO_y$ sample ZrO_2 sample

- $HfSi_xO_y$: RTA (1000 °C 60 s) to crystallize the films.
- ZrO_2: RTA in Ar atmosphere at 450 °C for 30 s.

TUNA measurement

- Dimension ICON with NanoScope V controller (closed –loop system) and Extended TUNA module.
- Pt/Ir coated Si probe (nominal tip radius of 25 nm)
- For all local *I-V* measurements, substrate bias was ramped from 0 V to – 10 V.

Experimental Parameters	$HfSi_xO_y$	ZrO_2
substrate voltage for TUNA current map (V)	-9.1	-2.7
tip velocity for TUNA current map (μm/s)	1.5	1.5
ramp rate for local IV measurement (V/s)	0.5	0.25
deflection setpoint (V)	-0.9	2.0

High resolution TEM analysis

- FEI CM 300 system
- Cross sectioned ZrO_2 sample

Results and Discussion

$HfSi_xO_y$ sample

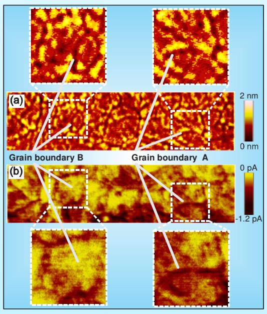


Figure 1. (a) TUNA topography map and (b) corresponding TUNA current map of the $HfSi_xO_y$ film. Scan size: 2 x 0.5 μm^2

Topography map (Fig. 1(a))

- Crystalline grains can clearly be observed in the topography.
- Height of grain boundaries is lower than that of grains.

TUNA current map (Fig. 1(b))

- Clearly visible conductive structures correspond to grain boundaries in topography map.
- Two types of grain boundaries are observed:
  - boundaries with high leakage current (grain boundary A)
  - boundaries with low leakage current (grain boundary B)

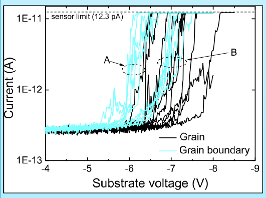


Figure 2. Local TUNA *I-V* curves through grains and grain boundaries.

Local *I-V* curves (Fig. 2)

- Distribution of local *I-V* curves at grains has wide spread, while that at grain boundaries shows two tight spreads (i.e., A and B)
- The two types of spreads might be due to different current conduction mechanisms for grain boundaries A and B, respectively (see Fig. 1).

- Leakage currents through grain boundaries are found to start at lower voltages for spread A.
- It is, however, difficult to clarify the origin of the difference for the *I-V* curves between grains and grain boundaries because of the effect of the thickness variations on the *I-V* curves.

ZrO_2 sample

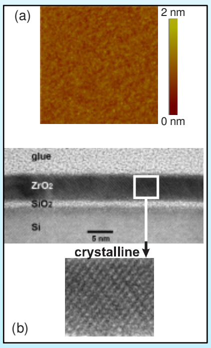


Figure 3. (a) Topography map of the ZrO_2 film measured by tapping mode AFM. Scan size: 500 x 500 nm^2, (b) HR-TEM image of the film.

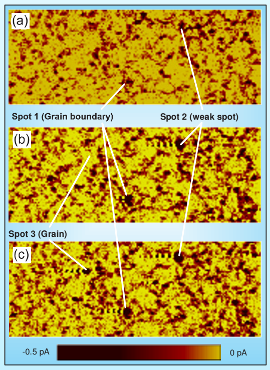


Figure 4. TUNA current maps (a) before any local *I-V* measurement, (b) after the 1st local *I-V* curve at a grain boundary (spot 1), (c) after the 2nd local *I-V* curve at a grain (spot 3). Scan size: 1.33 x 0.5 μm^2.

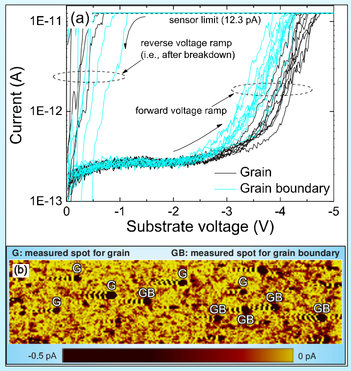


Figure 5. (a) local *I-V* curves for the ZrO_2 film at grains and grain boundaries. (b) TUNA current map after several local *I-V* measurements at grains and grain boundaries. Scan size: 1.33 x 0.5 μm^2.

Topography map (Fig. 3a) and HR-TEM image (Fig. 3b) of ZrO_2 film

- No crystal grains and smooth surface (RMS is 0.18 nm) observed by tapping mode AFM.
- HR-TEM image clearly shows nanocrystalline structure, and very smooth surface of ZrO_2 and underlying SiO_2.

TUNA current map before and after local *I-V* measurement at grain and grain boundaries (Fig. 4, Fig. 5 (b))

- Grains and grain boundaries can clearly be observed in the initial TUNA current map (Fig. 4 (a)):
  - Larger leakage current paths at grain boundaries in spite of the smooth the surface of the ZrO_2
- Points where local *I-V* curves have been performed before, can clearly be observed in subsequent TUNA current maps:
  - Very high leakage current with an oscillating noise along the scan direction due to breakdown of the spots (Fig. 4 (b,c)).
- Resolution of the TUNA current map is not deteriorated after local *I-V* measurements.

Local *I-V* curves for the ZrO_2 film at grains and grain boundaries (Fig. 5 (a))

- Significant differences between curves at grains and grain boundaries.
- Leakage current through the grain boundaries is up to 8 times larger than that through the grains at a voltage of -3.5 V.

Summary and Conclusions

$HfSi_xO_y$ film

- Topography map and leakage current distribution of the $HfSi_xO_y$ thin film could be simultaneously measured by TUNA.
- Leakage current through grain boundaries was found to be lager than that through grains.
- Two types of grain boundaries in terms of local *I-V* characteristics could be distinguished.

ZrO_2 film

- Major leakage current paths were located at the grain boundaries although surface morphology of the ZrO_2 film was rather smooth.
- Lager leakage current at grain boundaries is not due to a thickness variation of the film.
- *I-V* curves exactly located at grains and grain boundaries could successfully be measured.
- Local *I-V* curves show a significant difference between grains and grain boundaries.

This work was partially funded by the German Federal Ministry of Education and Research (BMBF) (Contract No. 01M3089E) within the project UTTERMOST (UlTimaTe Enablement Research on 32/28 nm MOS Technologies).

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