Fabrication of Zinc Oxide Thin Films for Acoustic Resonators

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550 °C

ZnO
Pt
SiO₂
Si

top view
cross-section
Collaborators

film deposition
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leakage current measurements
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piezoelectric measurements
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Raman scattering
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SEM images
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TEM images
Matt Libera - Stevens

X-ray diffraction
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TFR devices
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SAW devices
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thickness calculations
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Outline

Motivation
- Wireless Communication
- SAW and TFR devices
- Materials Constraints
- Materials Selection and Optimization

Experimental
- Sputter chamber configuration

Results
- Film characterization
- X-ray diffraction (orientation and crystallinity)
- Raman scattering (crystallinity)
- SEM images (morphology)
- TEM images and ED (morphology and defect structure)
- Electrical leakage current measurements (stoichiometry)
- Piezoelectric displacement
- TFR performance

Summary
RF Filters for Cellular Phones

Thin Film Resonator based Bulk Acoustic Wave filters.

courtesy of B. Barber and G. Rittenhouse
Device Motivation

**Surface Acoustic Wave (SAW) Devices**
- bulk device (single crystal piezoelectric)
- thin film on high acoustic velocity substrate
  
  *Advantage* - flexibility by electrode patterning
  
  *Disadvantages* - low power, f limited by LW

  - diamond has not demonstrated low insertion loss, may be expensive
  - LiTaO$_3$ cannot operate at high f and power

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**Thin Film Resonator (TFR) Devices**
- solidly mounted resonator (SMR)
- film bulk acoustic resonator (FBAR)
- membrane resonators
  
  *Advantages* - low insertion loss, high power
  
  *Disadvantage* - film thickness uniformity
Materials Constraints

Best devices are made with stoichiometric single crystal thin films having minimal defects.

Substrate Requirements:
- Lattice matched
- Thermal expansion matched
- Atomically smooth
- Uniformly terminated

Substrates that I am required to use:
- SAW - diamond - polycrystalline and rough
- TFR stack - amorphous

Therefore, the best thin film attainable will be polycrystalline and possibly oriented (textured).
Zinc oxide (ZnO) was chosen because it has the highest piezoelectric coupling coefficient (excluding ferroelectrics which demonstrate fatigue, that is a decrease in the coupling coefficient with time).

**Optimization of ZnO Thin Films**

- **high piezoelectric coupling coefficient ($k^2$)**
  - Highly oriented with $c$-axis normal to the substrate
  - Minimal defects (stacking faults, dislocations)

- **high electrical resistivity of the film**
  - Stoichiometric (Zn:O = 1:1)
Sputter Chamber Geometry

Target material:
- Zn
- ZnO

Deposition conditions:
- 2 kV
- 75 W
- Ar/O₂ 5 sccm each
- 6 mTorr

Thin film microstructure and properties depend on the following:
- substrate temperature during deposition
- Pt nucleation layer
- radial position on substrate
- target composition
- sputtering power
- partial pressure of oxygen during deposition
X-ray Diffraction ($\theta$-2$\theta$ scan)

Dramatic improvement in crystallinity upon heating.

Zn metal target

400 C
500 C
550 C
600 C
650 C
700 C

400 C
700 C

ZnO 0002
Pt 111
ZnO 0004
Si 400
Pt 222
X-ray diffraction (0002) Intensity

Intensity ZnO 0002 (cps)

Substrate Deposition Temperature (°C)

linear scale
ZnO (0002) reflection

Rocking curve for a ZnO film deposited at 650 °C on Pt (111)

ZnO rocking curves versus deposition temperature

FWHM=1.42°
Raman Scattering

E₂ Raman mode
only Raman active

Normalized Intensity

Wavenumber (cm⁻¹)

50 °C

400 °C

0 0.2 0.4 0.6 0.8 1

GK #49 on Pt
GK #101 on Pt
ZnO single crystal
ZnO Film Morphology

Effect of Substrate Temperature

Top Surface

Cross Section
Comparison between SZMs

Movchan & Demchishin

Thornton

Messier et al.

This study
TEM ZnO $T_{\text{dep}} = 600$ °C

Dislocations observed
- large lattice mismatch (-14.6%)

Sharp diffraction reflections
TEM ZnO $T_{\text{dep}} = 45 \degree C$

Reflections observed in diffraction
Not amorphous!
-reflections have broader width due to diffraction from several slightly misoriented grains

Stacking faults observed
No amorphous region at interface
Leakage currents in Pt/ZnO/Pt capacitors

Current measured along ZnO c-axis

Averaged over several grains (current flows within single grain)

• steady-state leakage currents for films deposited at high substrate temperatures
• transient leakage current for films deposited at low substrate temperatures
Resistivity of ZnO films

- Saturation in resistivity due to transient behavior - value determined by measurement wait time and history.
- Number of carriers increasing exponentially as substrate temperature increases.

Graph showing the relationship between substrate temperature during deposition (°C) and resistivity (ohm-cm).
Piezoelectric Displacement

Vibration amplitude in a 40x40 μm sector of a circular electrode.
Piezoelectric Performance

![Piezoelectric Performance Graph](image)

- **Piezoelectric Displacement (Å/V)**
  - x-axis: Substrate Temperature during Deposition (°C)
  - y-axis: Piezoelectric Displacement (Å/V)
TFR Device Morphology

Si Substrate

TFR top electrode

TFR cross section

\( \lambda/2 \) piezoelectric layer
Pt nucleation layer

\( \lambda/4 \) reflecting stack
Log of \textbf{Mag} \( z \) and \textbf{Phase} \( z \) vs Frequency (GHz)

Center frequency 3.1 GHz
BW = 97 MHz = 3.03%
Summary

Deposited ZnO thin films by reactive sputtering.

Determined correlations between various processing parameters and ZnO film properties.

Obtained control of crystallinity, morphology, resistivity, and piezoelectric performance.

Optimized ZnO film properties for piezoelectric applications.

Demonstrated excellent bandwidth in a prototype TFR.