# Device Research for the MUSE Initiative

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# Objective

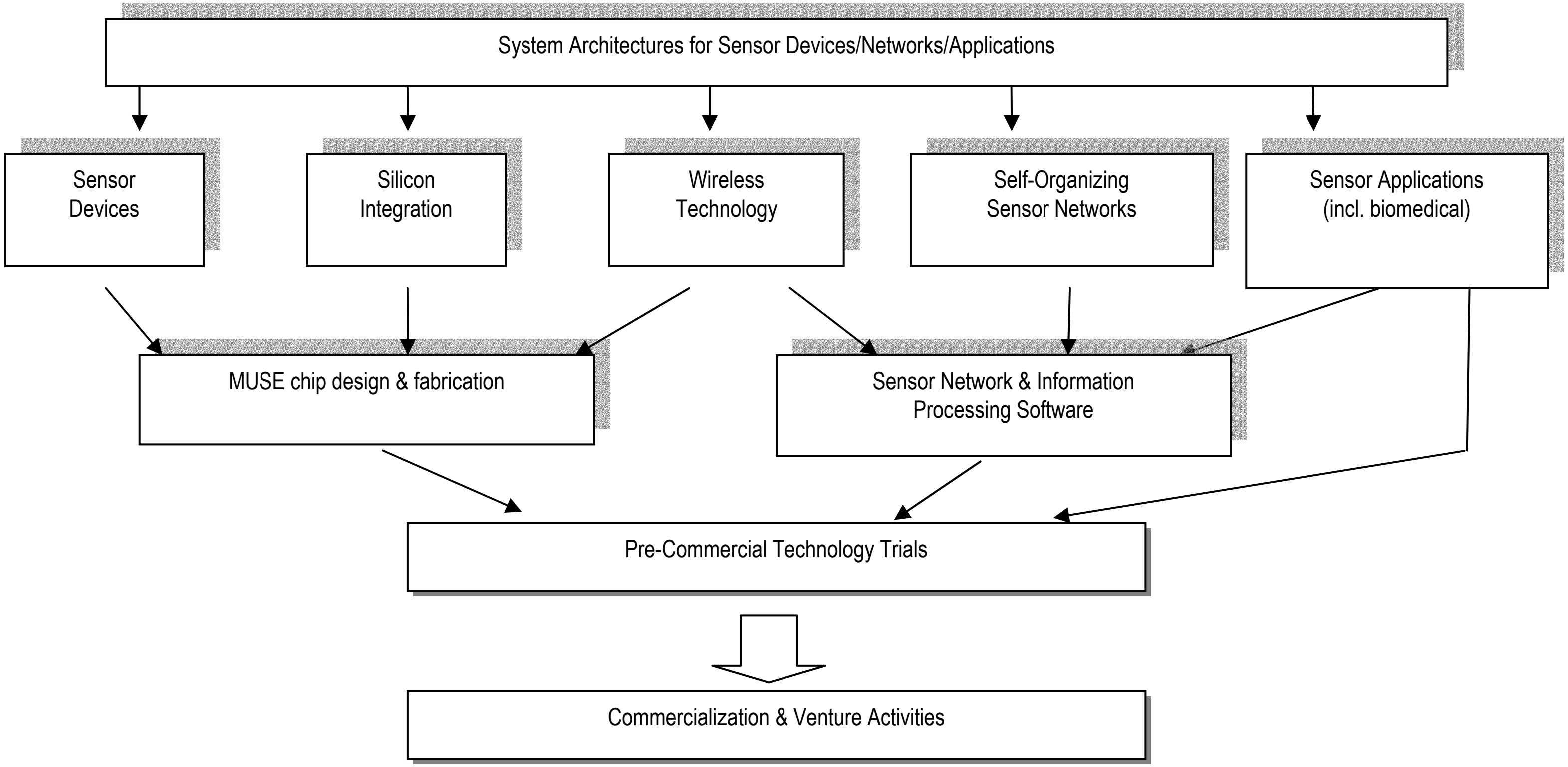
- Establish an interdisciplinary R&D Excellence Center for hosting collaborative research towards the development and transfer of <u>mu</u>ltimodal integrated wireless <u>se</u>nsor-on-silicon (MUSE) technology.

## Focus on the following areas:

- Device technologies for multimode sensor modules (RF, optical, acoustic, mechanical & biochemical)
- Integrated sensor-on-silicon architecture for multi-modal wireless sensors
- Wireless communication module for low-cost, robust, self-organizing sensor networks
- Sensor network architecture, protocols and information processing software
- End-user applications and trials using prototype MUSE devices (with initial focus on biomedical uses)

# Proposed Research Initiative

## CENTER FOR MULTI-MODAL WIRELESS INTEGRATED SENSOR-ON-SILICON (MUSE) TECHNOLOGY


System Architectures for Sensor Devices/Networks/Applications

Sensor Devices

Silicon Integration

Wireless Technology

Self-Organizing Sensor Networks

Sensor Applications (incl. biomedical)

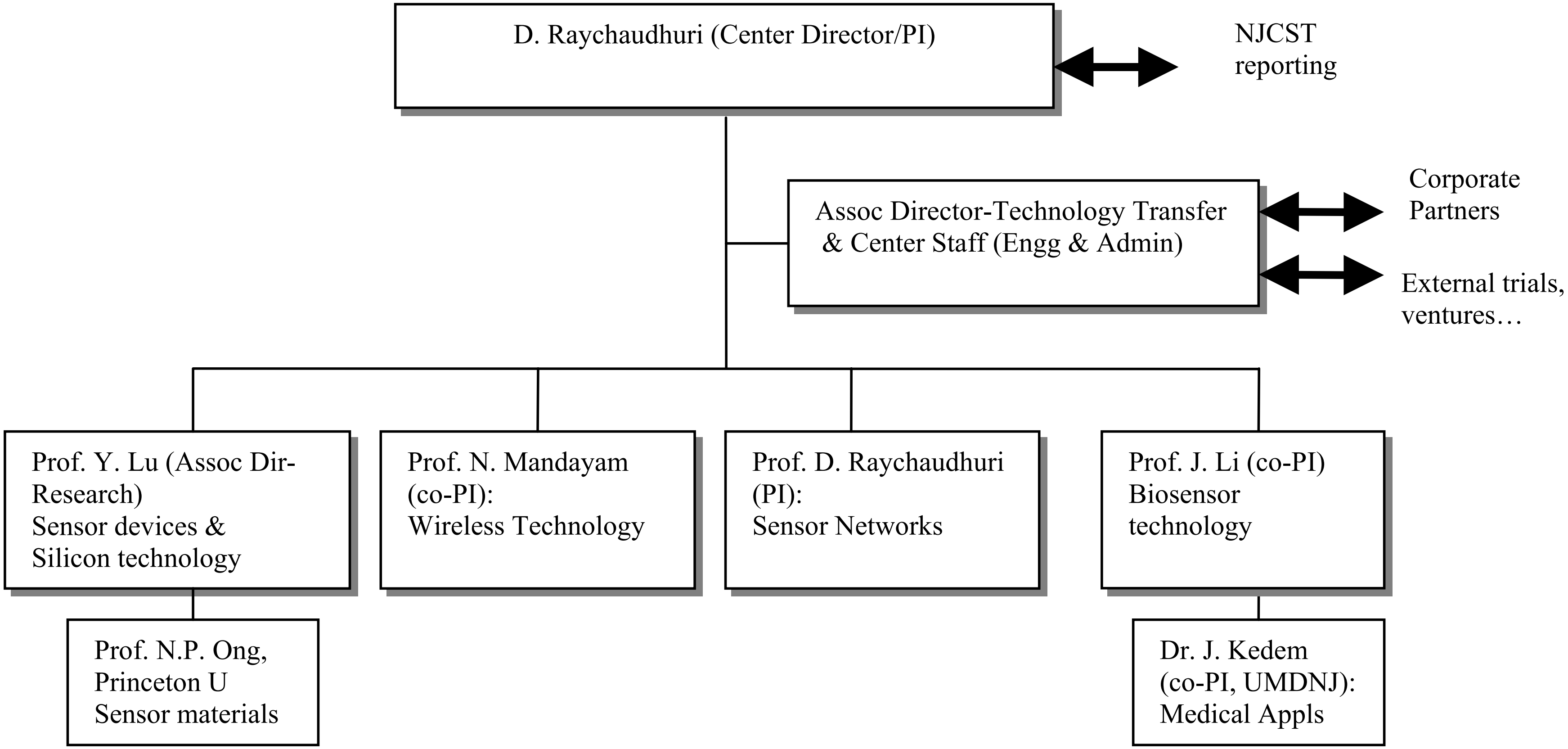
MUSE chip design & fabrication

Sensor Network & Information Processing Software

Pre-Commercial Technology Trials

Commercialization & Venture Activities

# MUSE Research Team



D. Raychaudhuri (Center Director/PI)

NJCST
reporting

Assoc Director-Technology Transfer
& Center Staff (Engg & Admin)

Corporate
Partners

External trials,
ventures…

Prof. Y. Lu (Assoc Dir-Research)
Sensor devices &
Silicon technology

Prof. N.P. Ong,
Princeton U
Sensor materials

Prof. N. Mandayam
(co-PI):
Wireless Technology

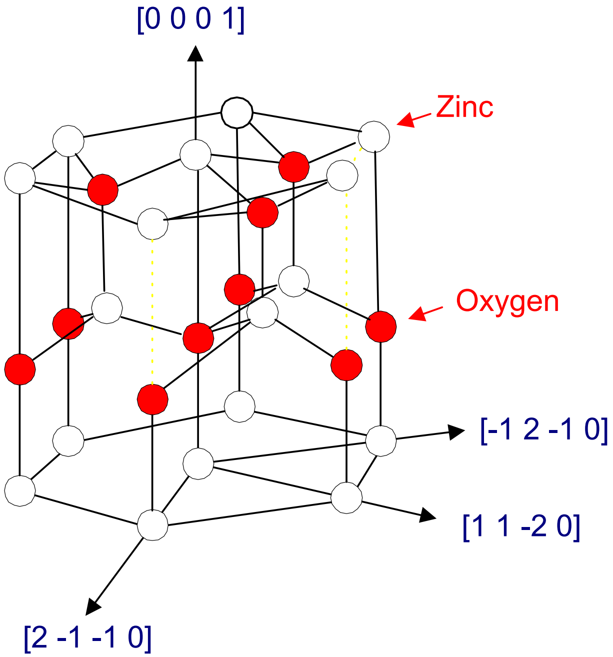
Prof. D. Raychaudhuri
(PI):
Sensor Networks

Prof. J. Li (co-PI)
Biosensor
technology

Dr. J. Kedem
(co-PI, UMDNJ):
Medical Appls

# Introduction: ZnO Materials

- II-VI compound semiconductor.
  - Direct bandgap, with $E_g \cong 3.32$ eV.
  - Bandgap engineering: alloy with Cd or Mg to tailor bandgap from 2.8eV to 4.0eV.
- Multi-functional:
  - Hexagonal wurtzite class crystal => piezoelectricty with large coupling coefficient.
  - Large and fast photoconductivity => optical sensing.
  - Al or Ga doping => transparent conductive oxide.
  - Li & Mg doping => ferroelectric.
  - Alloyed with Mn => magnetic oxide semiconductor.
- Integrate electrical, optical and piezoelectrical properties => MITSAW chip technology

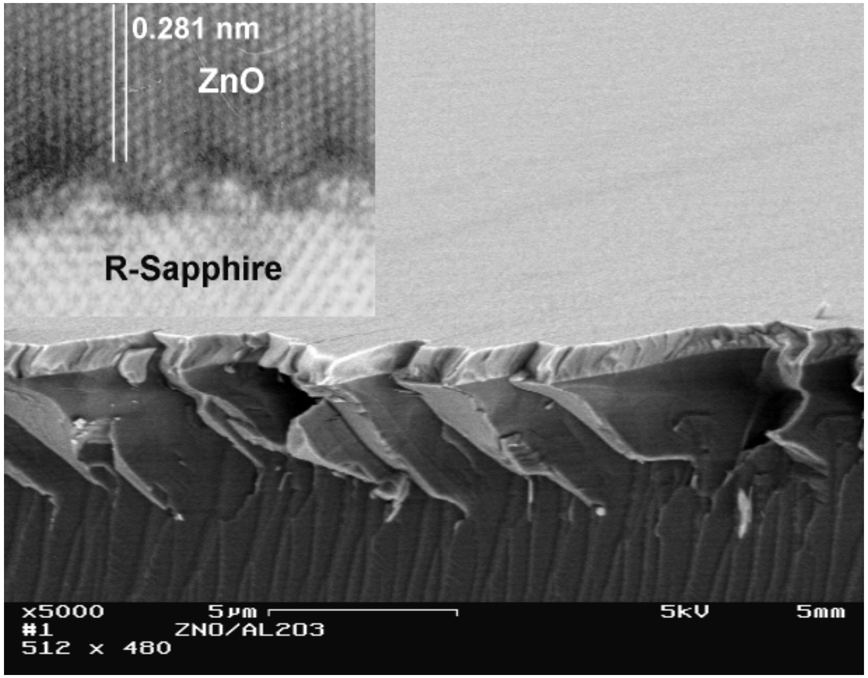


# Achievements of ZnO Research at Rutgers

- High quality MOCVD ZnO and $Mg_xZn_{1-x}O$ thin films on R-$Al_2O_3$ and $SiO_2$/Si.
- Low loss ZnO/R-$Al_2O_3$ SAW devices.
- The first high speed ZnO MSM photoconductive and Schottky UV photodetectors.
- The first optically addressed normal incidence ZnO UV high contrast modulator.
- The first ZnO Schottky devices on R-$Al_2O_3$.
- Novel ZnO nanostructures.
- Novel MITSAW chip technology.

# ZnO Growth on R-$Al_2O_3$

- Metalorganic chemical vapor deposition (MOCVD):
  - Precursors: Diethylzinc (DEZn), $(MCP)_2Mg$, $O_2$
  - ECR microwave plasma
- Atomic scale sharp ZnO/ R-$Al_2O_3$ interface, semicoherent.
- Photoluminescence:
  - 6 meV @ 11K.
  - Bulk ZnO 3 meV @ 4.2K.



# Challenges for Biosensors

- Integration of sensors to obtain multiplexed functionality
- Development of sensor interface o relate its output to physiologically or clinically meaningful parameters
- Reduction or elimination of sensor biofouling
- Develop wireless networking technology for sensors
- Ensuring a cost-effective solution

# SAW Sensors: Dual Channel Oscillator

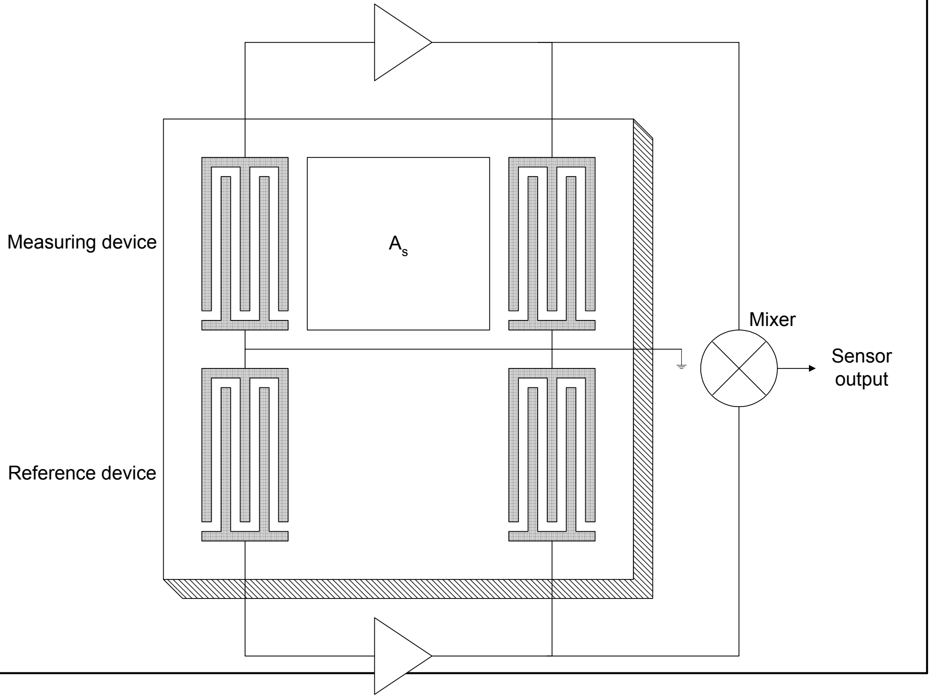
- Selective coating placed between the two IDTs of the measuring SAW device.
- Mass loading effect will change the center frequency of the oscillator circuit.
- Reference device to eliminate deviations due to external effects.
- Sensor output =

frequency difference between

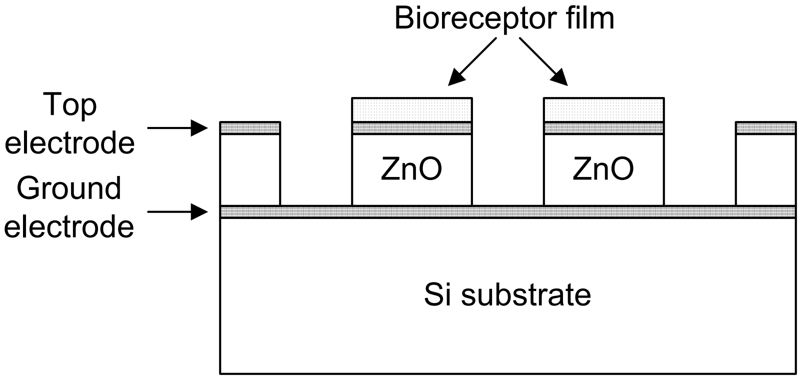
the two oscillator circuits.

- Can be arrayed to obtain

multi-channel arrays.



# Micromachined BAW(TFR) Sensor Arrays



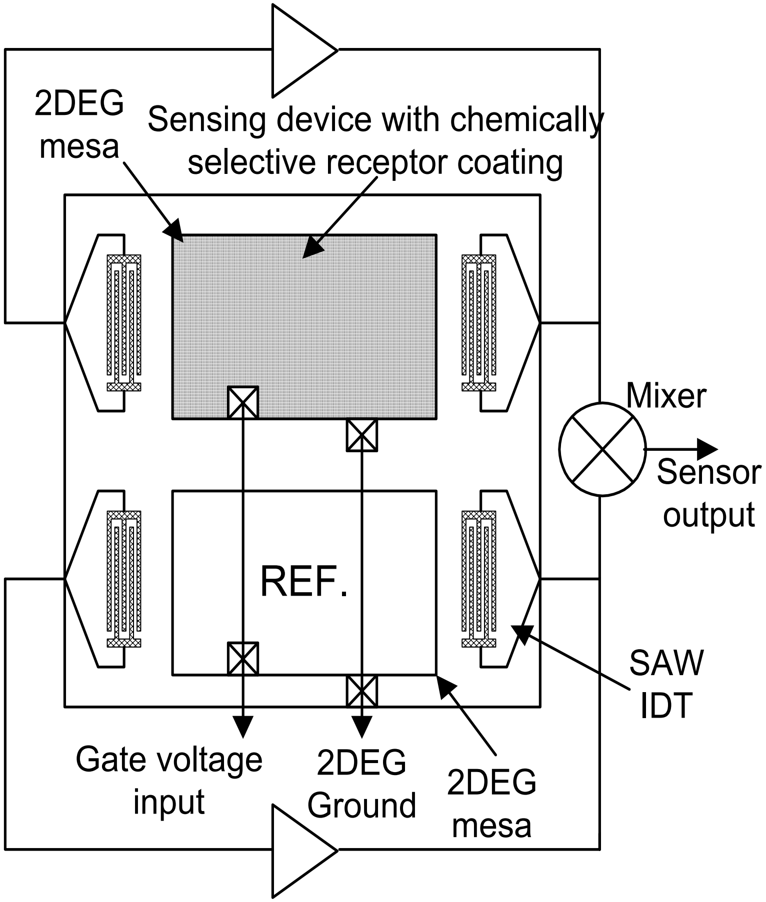
- An array of micromachined thin film resonators (TFRs) will selective coatings.
- A large number of target materials can be detected and measured on the surface area of the same chip.
- Can be integrated with electronic circuits => smart sensor.
- Dramatically improve sensor reliability and allow detection and measurement of multiple chemicals simultaneously.

# MITSAW Operation and Advantages

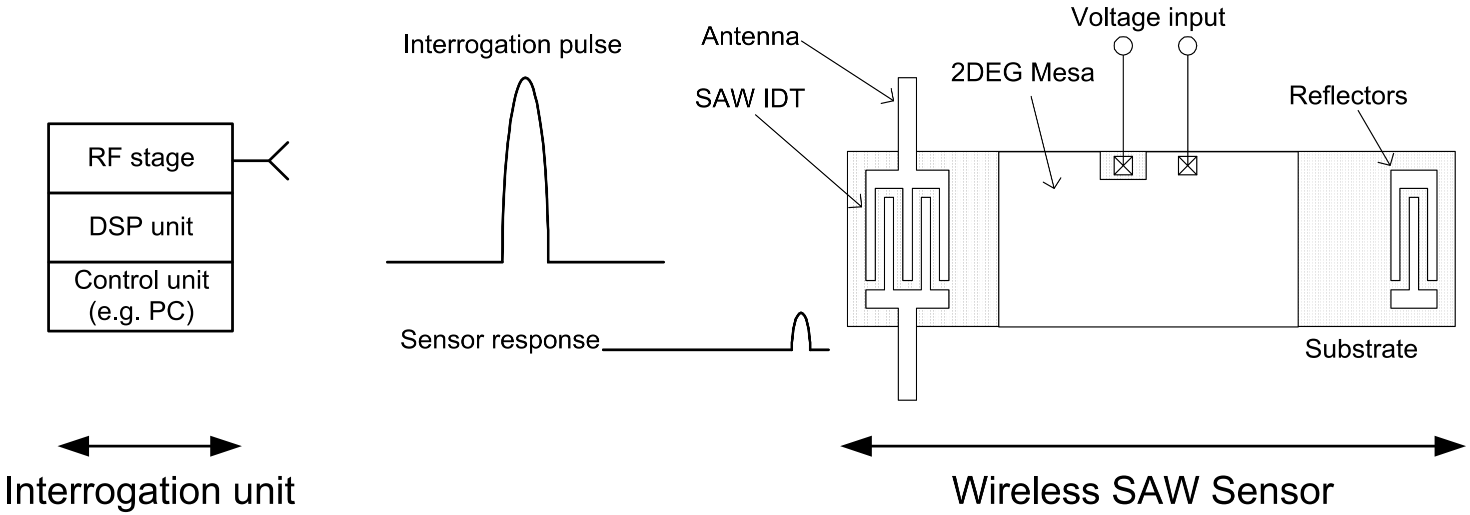
- Operation:
  - Integration of 2DEG and SAW in the ZnO/R-$Al_2O_3$ material system.
  - Interaction of the electronic field of SAW with 2DEG results in slowing of the SAW velocity.
  - 2DEG density is controlled by reverse bias voltage across the Schottky barrier, thus the acoustic velocity can be controlled by the bias voltage.
- Advantages:
  - Excellent manufacturability, high yield and low cost.
  - High electromechanical coupling coefficients and high SAW velocity ⇒ high frequency and low loss RF devices.
  - The in-plane anisotropy of electrical, optical and acoustic properties.
  - Multi-functionality and broad applications.

# MITSAW Application to Biosensors

- MITSAW sensor can be "reset" by tuning SAW velocity, therefore, increases the sensor lifetime.
- Multiple wave modes for increased sensitivity in gas or liquid sensing environment.
- Dual mode (acoustic and UV optic) operation: to improve identification and sensitivity.



# Zero-Power Remote Wireless Sensors

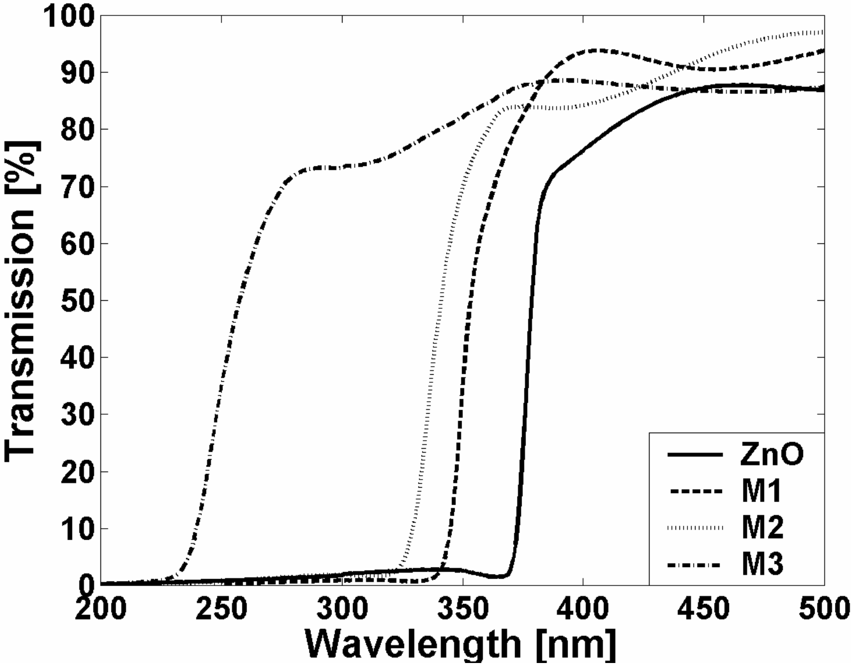


- Base station sends interrogation pulse.
- The antenna picks the pulse; the SAW IDT launches a wave packet.
- The wave packet travels across the delay path, is reflected by the reflecting array.
- The reflected wave generates a signal at the IDT.
- The antenna send a response pulse.
- 2DEG bias determines acoustic velocity, hence response delay time.
- Thus the device is a wireless read-out element for a voltage-generating sensor.

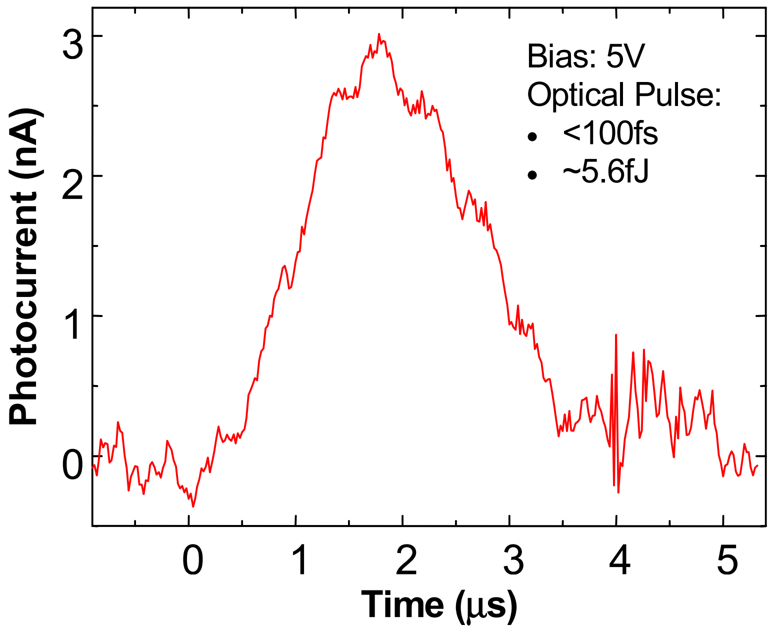
# $Mg_xZn_{1-x}O$ UV Detectors

- Applications:
  - Biosensors (biochemicals have unique UV spectra)
  - Environmental monitoring and protection (chemical, fire, smoke, etc.)
  - Aerospace engineering (solar-blind, UV sensitive)

ZnO 373 nm
M1 345 nm
M2 329 nm
M3 240 nm



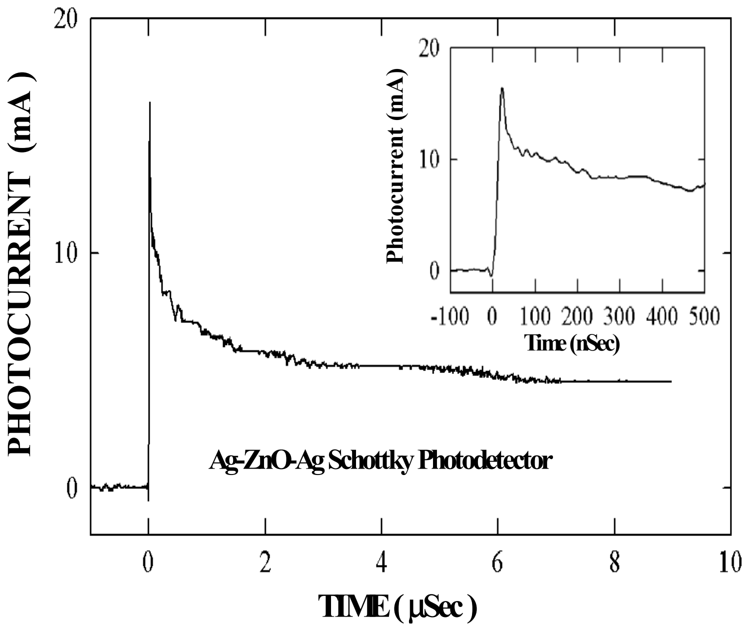
# Photocurrent vs. Response Time of a Photoconductive and Schottky Photodetector



**A.Photocurrent vs. Response Time of a Photoconductive Photodetector**

**Rise Time: 1µs**

**Fall Time: 1.5µs**



**B.Photocurrent vs. Response Time of a Schottky Photodetector**

**Rise Time: 12ns**

**Fall Time: 50ns**

# Integrating ZnO with Si: Advantages

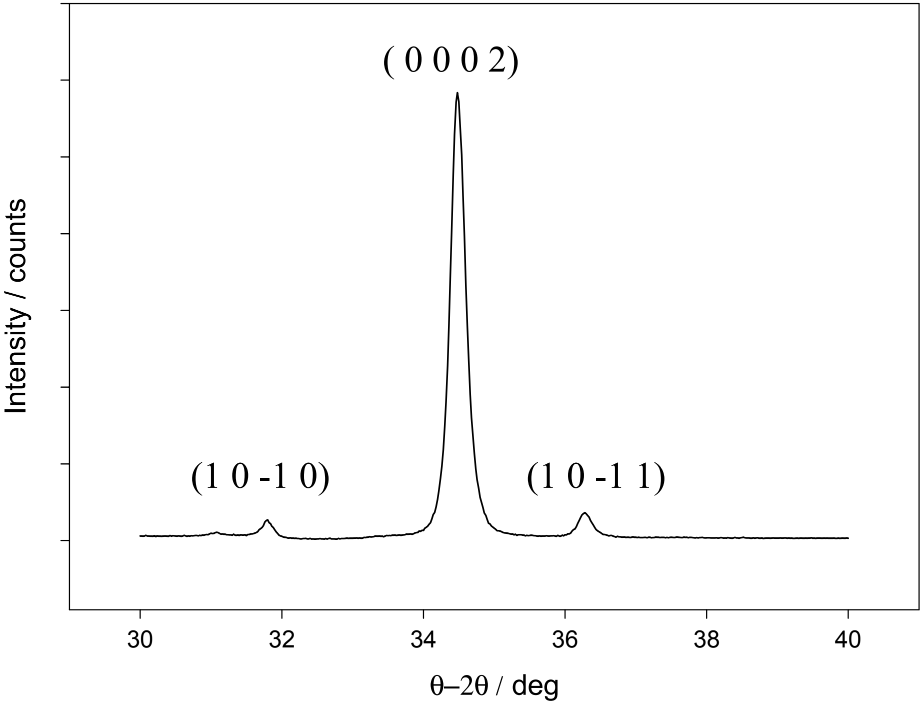
- SAW devices can be integrated with Si ICs.
  - Almost all ICs use a Si substrate.
  - Thermally grown $SiO_2$ is available in most IC processes.
- The $SiO_2$ acts as a temperature compensation layer to improve the temperature stability.
  - ZnO and Si have positive temperature coefficient of delay (TCD).
  - $SiO_2$ has negative TCD.
- Temperature compensated frequency responses can be obtained by optimizing the ZnO to $SiO_2$ thickness ratio.
- MOCVD growth of ZnO is done at low temperatures, therefore junction movement is minimized.

# Integration with Si: Two-Step ZnO Growth

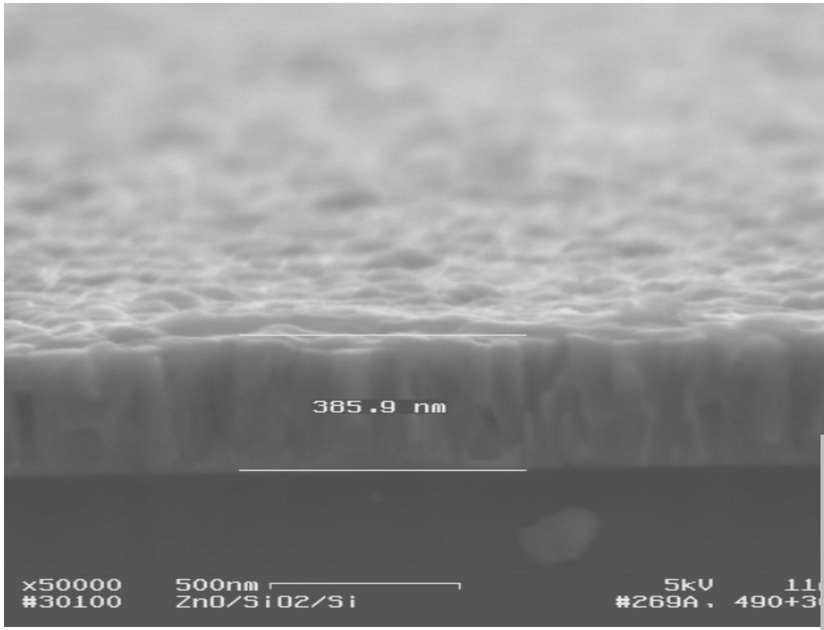
- **High growth temperature:** predominantly c-axis oriented, rough surface morphology.
- **Lower growth temperatures:** smooth surface morphology, poor crystallinity.

**Two-Step Growth:**

- Relatively high T buffer layer => stable crystalline template for subsequent low T step.
- Crystallinity maintained: ZnO film that nucleates on the buffer layer continues the atomic arrangement of the previous layer.

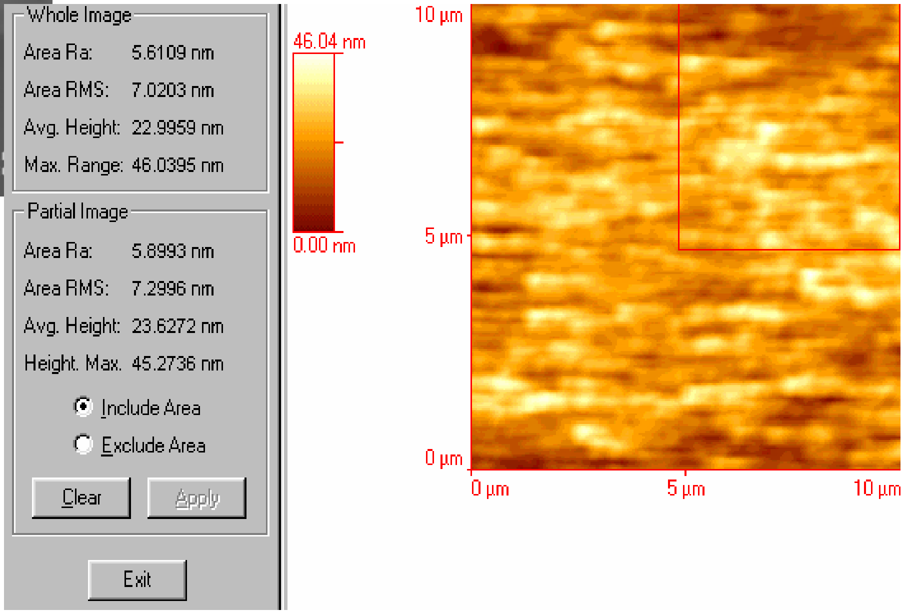


# Two-Step Growth of $ZnO/SiO_2/Si$



- The ZnO buffer layer is initially grown at 490°C for 1-5 mins. followed by a top layer grown at 300°C-340°C.

- The films are highly c-axis oriented.
- The surface morphology is very smooth with an average RMS roughness of 7nm.



Whole Image
Area Ra: 5.6109 nm
Area RMS: 7.0203 nm
Avg. Height: 22.9959 nm
Max. Range: 46.0395 nm

Partial Image
Area Ra: 5.8993 nm
Area RMS: 7.2996 nm
Avg. Height: 23.6272 nm
Height. Max. 45.2736 nm

● Include Area
○ Exclude Area

# Patents and Invention Disclosures

## Related Patents

- “High Contrast, Ultrafast Optically Addressed Ultraviolet Light Modulator Based Upon Optical Anisotropy in ZnO Films Grown on R-plane Sapphire” (with M. Wraback, H. Shen, S. Liang and C.R. Gorla), Aug. 17, 1999, Provisional Patent Application ARL 99-66
- “Monolithically Integrated Tunable Surface Acoustic Wave Technology and Electrical Systems Provided Thereby” (with N.W. Emanetoglu), filed July 13, 2001
- “Surface Acoustic Wave Technology and Sensors Provided Thereby”, (with N.W. Emanetoglu), filed July 13, 2001

## Recent Invention Disclosures

- “Fabrication of Ag Schottky contacts on () $Mg_xZn_{1-x}O$” (with H. Sheng, S. Muthukumar, N.W. Emanetoglu, J. Zhong), filed Dec. 2001
- “Tailoring Piezoelectric Properties Using $Mg_xZn_{1-x}O$ and $Mg_xZn_{1-x}O/ZnO$ Structures” (with N.W. Emanetoglu), filed Dec. 2001
- “Selective Growth and Fabrication of ZnO Single Nanotip and ZnO Nanotip arrays” (with S. Muthukumar), filed Feb. 2002

# Conclusions

1. ZnO is a promising sensing material:
    - Multifunctionality
    - Tunability/ Resetability (reducing biofouling)
    - Integratabile with Si and Si-on-Sapphire substrates
    - Manufacturability (low cost)
2. ZnO based sensor devices have broad applications:
    - UV sensors (biochemical, aerospace, etc.)
    - Biosensors (SAW, BAW, nanotip)
    - Wireless passive sensors (zero power consumption)
    - Magnetic sensors (spintronics)
    - High energy particle sensors (radiation-hardness)
    - MITSAW sensors (multifunctional, resetable, tunable)

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