Overview of ZnO Based Materials and Device Research at Rutgers

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Rutgers Research Group

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Rutgers Facilities -1

- Processing and Fabrication:

  Microelectronics Research Laboratory (MERL) is a class 100/1000 clean room.
  - Plasma-enhanced MOCVD and low-pressure CVD
  - E-beam evaporation and sputtering
  - Thermal oxidation and diffusion furnaces
  - Photolithography

- Coming soon:
  - Sputtering system (RF and DC)
  - ICP and RIE plasma etchers
  - Plasma-enhanced CVD

Rutgers Facilities - 2

- Characterization
  - Material characterization: X-Ray, HR-TEM, FESEM
  - HP 8753D network analyzer and Cascade Microtech probe station
  - HP/Agilent I-V and C-V measurement units
  - Optical testing system, UV and visible range
- Simulation Hardware and Software
  - Sun and HP workstations, high performance PCs, Rutgers Supercomputing facility with Sun E10K
  - In-house pieozelectric materials and device simulators, commercial Silvaco, HP EESof, HP and Ansoft HFHSS software packages.

Research Projects

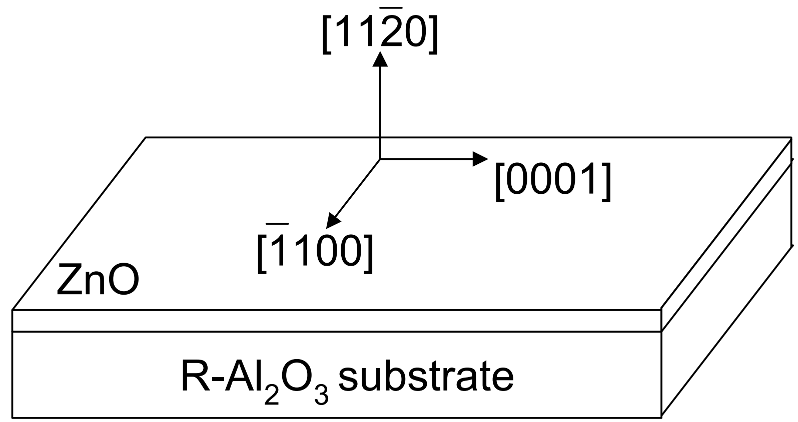
- MOCVD growth of ZnO and $Mg_xZn_{1-x}O$ on R-Al_2O_3
- Piezoelectric devices for communications/sensors:
  - Surface acoustic wave (SAW) devices
  - Bulk acoustic wave (BAW) thin film resonators (TFR)
  - Monolithically Integrated Tunable SAW (MITSAW) (NSF)
  - ZnO on SiO_2/Si for temperature compensated SAW
  - Programmable SAW filters
- Optoelectronic devices:
  - First high speed ZnO UV detectors (Schottky and PC)
  - First high speed, high contrast ZnO UV modulator
  - First ZnO Schottky diode
  - FET, HFET and device integration (recently started)
- Nanoscale materials and devices (NSF supported)

ZnO Material Properties

- 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 => piezoelectric (SAW,BAW)
  - Al or Ga doping => transparent conductive oxide
  - Li & Mg doping => ferroelectric (MEMS, sensors, memory, RF switching)
  - Alloyed with Mn => magnetic (MEMS, sensors, magneto-optical, switching)
- Has large piezoelectric coupling coefficient.
- Integrate semiconductor with piezoelectric => MITSAW.

Properties of ZnO films on R-Al_2O_3 Substrates

- c-axis of ZnO is in plane:
- Epitaxial relationship:
  $[11\bar{2}0]$ ZnO // $[01\bar{1}2]$ R-Al_2O_3
  $[0001]$ ZnO // $[0\bar{1}11]$ R-Al_2O_3
- Lower lattice mismatch:



Between $(11\bar{2}0)$ZnO and $(0\bar{1}12)Al_2O_3$

along [0001] of ZnO:

$$\frac{3c_{ZnO} - (\sqrt{3a_{sapphire}^2 + c_{sapphire}^2})}{\sqrt{3a_{sapphire}^2 + c_{sapphire}^2}} = 1.53\ \%$$

along $[1\bar{1}00]$ of ZnO:

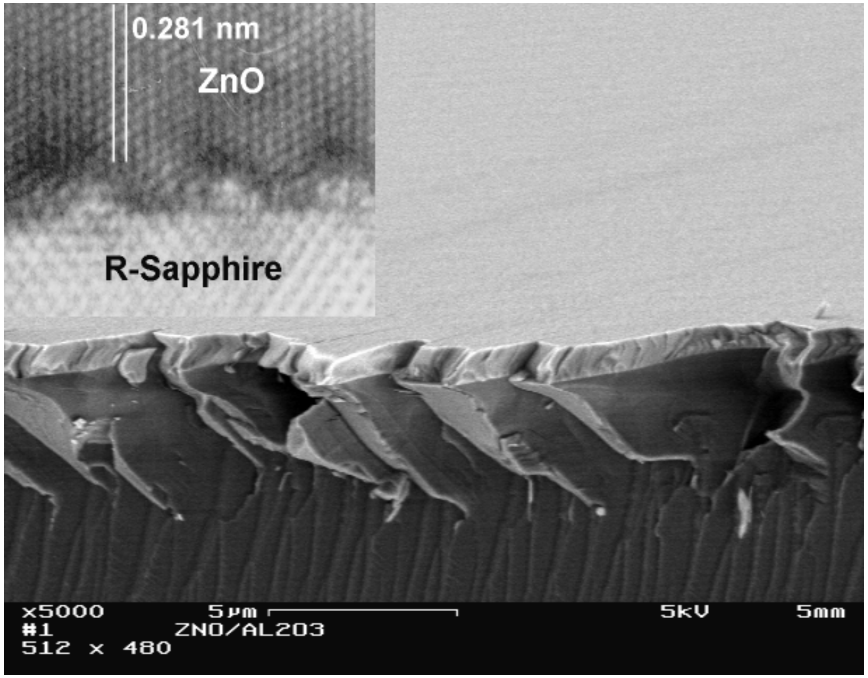
$$\frac{a_{ZnO} - (a_{sapphire}/\sqrt{3})}{(a_{sapphire}/\sqrt{3})} = 18.3\%$$

on C-Al_2O_3 : 18.3% mismatch in both in-plane directions

- In-plane anisotropy:
  - Electrical, optical and piezoelectric anisotropy.
  - Novel device concepts can be realized.

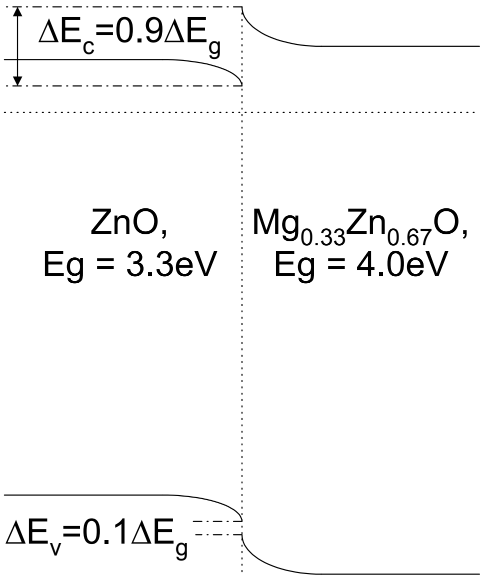
ZnO Growth on R-Al_2O_3

- 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.



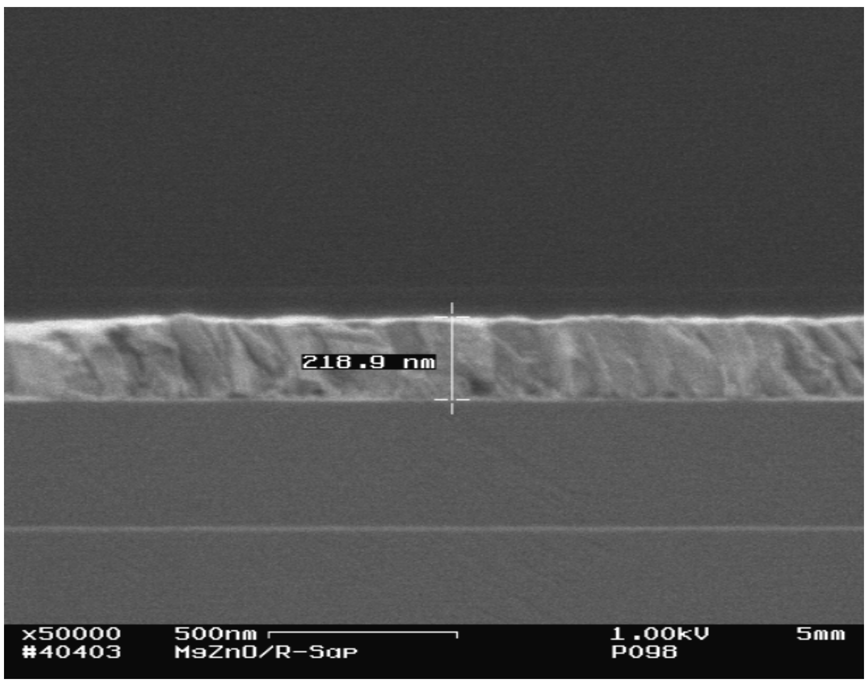
Fundamental Properties of $Mg_xZn_{1-x}O$

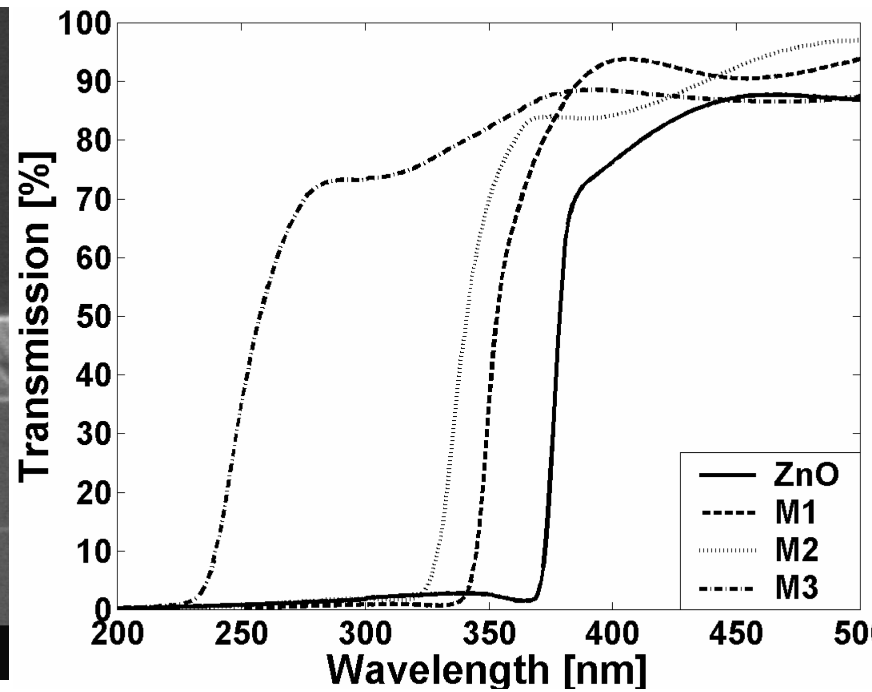
- MgO has cubic rocksalt crystal structure
  - Lattice Parameter 4.215 Å
  - similar Ionic radii: Mg^{+2}(0.71 Å) while Zn^{+2}(0.74 Å)
  - bandgap (E_g): 5.8 eV*
- c/a ratio decrease with Mg incorporation
- $E_g(Mg_xZn_{1-x}O) = [x \cdot 5.8 + (1-x) \cdot 3.32]$ eV
- $\Delta E_c = 90\% \, \Delta E_g$
- Thermodynamic solid solubility limit: ~5 mol % MgO in ZnO
- Epitaxial thin films have been grown with x > 33 mol%



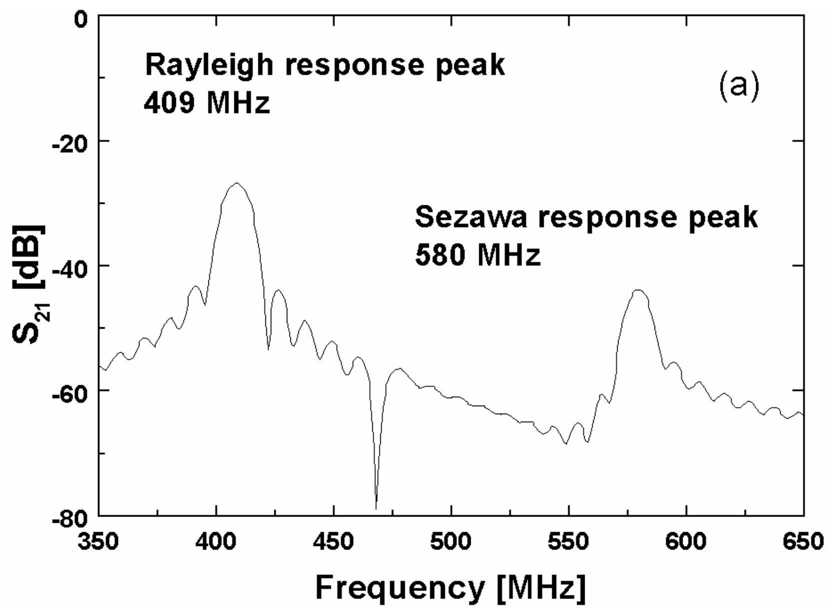
$Mg_xZn_{1-x}O$ Growth on R-Al_2O_3

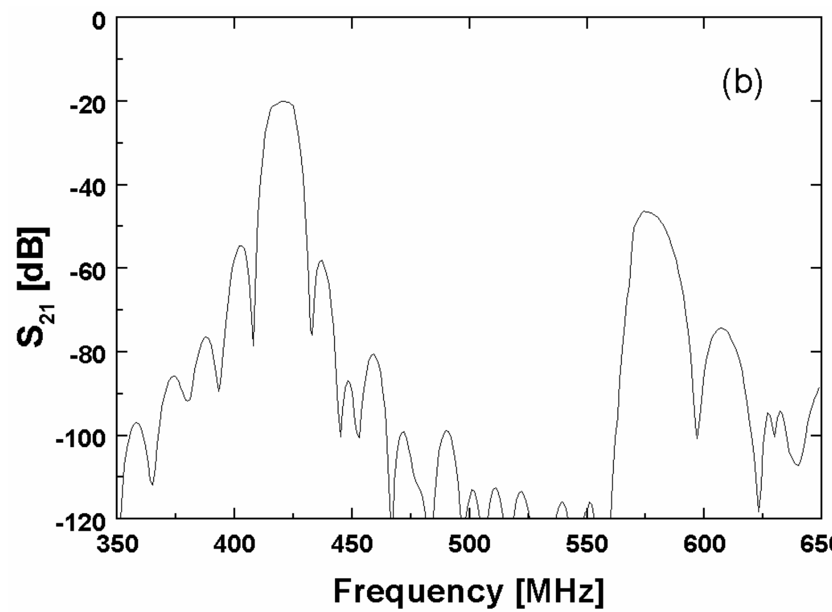
- $E_g(Mg_xZn_{1-x}O)$ = <u>$x \cdot 5.8\ eV + (1-x)\ 3.32\ eV$</u>
- Mg contents greater than 20% achieved.
- ZnO 373 nm; M1 345 nm; M2 329 nm; M3 240 nm



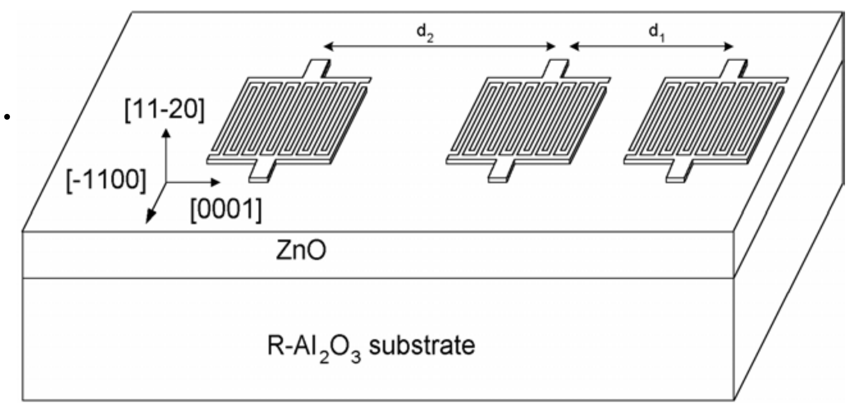


SAW Devices on the $ZnO/R\text{-}Al_2O_3$ System

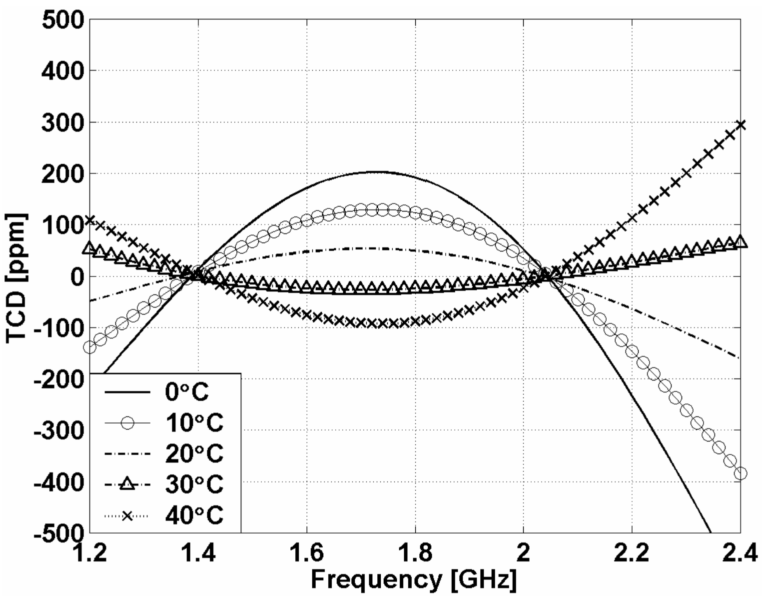


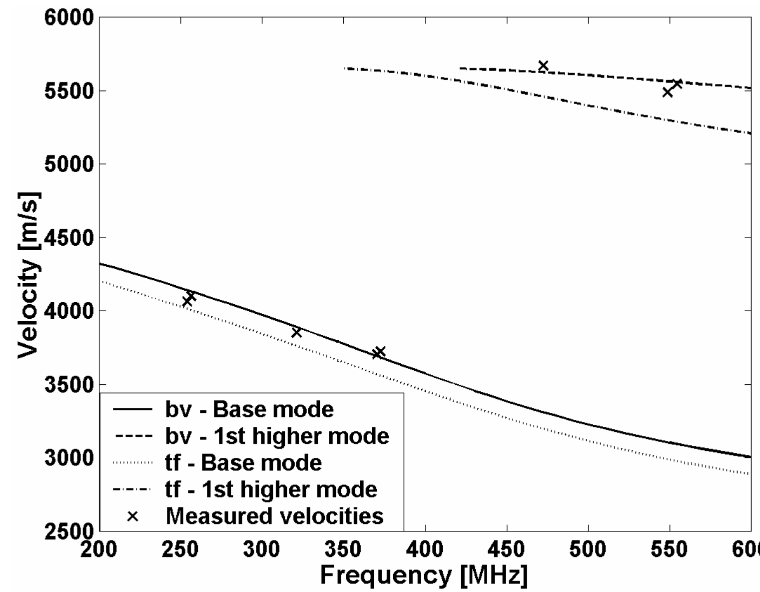


- Device alignment:
  //c: Rayleigh waves; ⊥ c: Love waves.
- λ_0 = 10μm, 16μm.
- k^2 up to 6% achieved.



$ZnO/SiO_2/Si$ for SAW

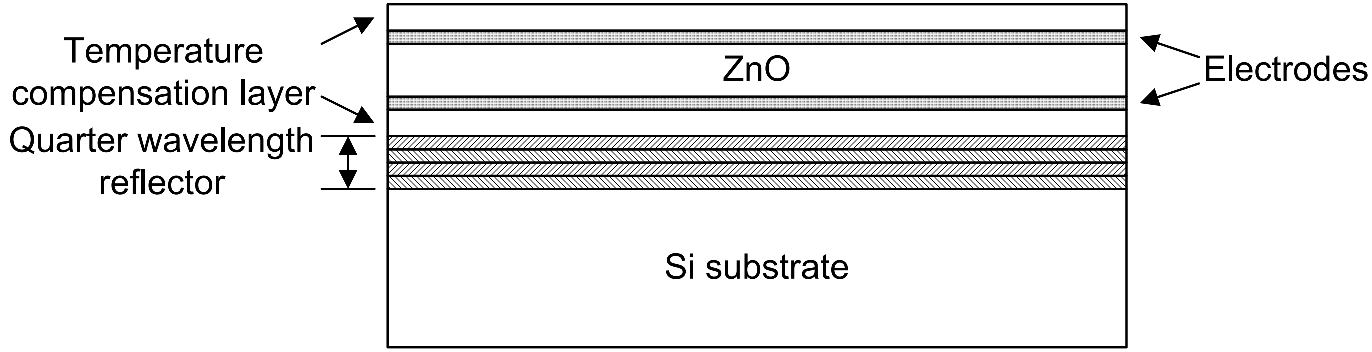




- Two temperature compensated points (simulated for $h_{ZnO}:h_{SiO2}$ = 2:1)
- 1.45 GHz:
  - SAW velocity: 5500.4 m/s
  - Coupling, k^2: 0.71%
- 2.05 GHz:
  - SAW velocity: 5089.6 m/s
  - Coupling, k^2: 0.82%

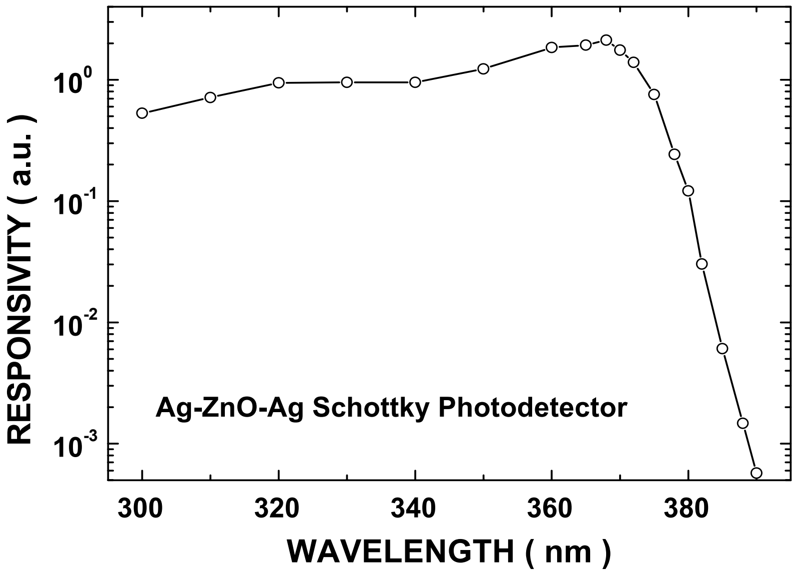
- Simulations done with both reported bulk and thin film ZnO values.
- Velocity dispersion data for base and 1st higher order GSAWs closely match simulations using bulk constants.
- This is expected due to the high quality of MOCVD grown ZnO film.

ZnO Thin Film Resonators (TFRs) Sensors



- High frequency (up to 16GHz) and low loss filters.
- Temperature compensation possible.
- Integratable with Si (low temperature process).
- Multiple TFRs can be used to detect and measure a wide range of chemicals/biochemicals on one chip.

Spectral Photoresponse of a ZnO Schottky PD with an IDT Structure



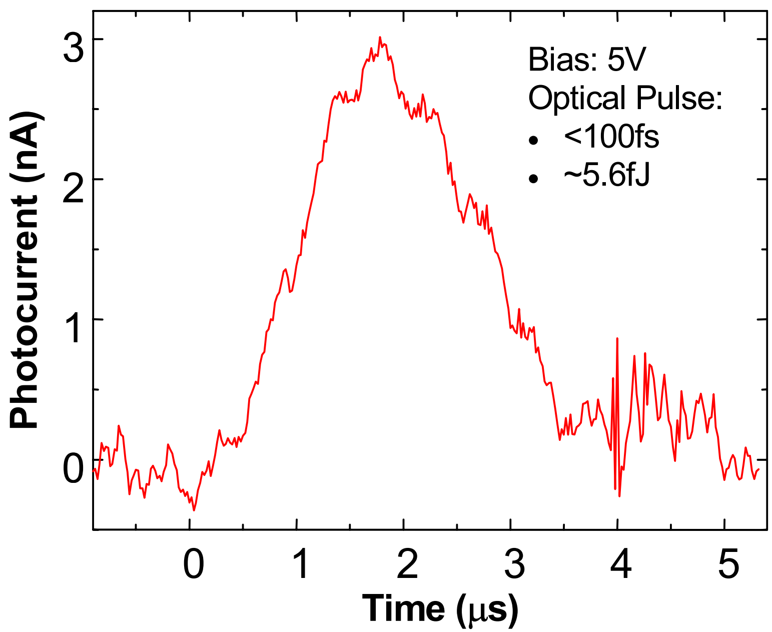
Advantages:

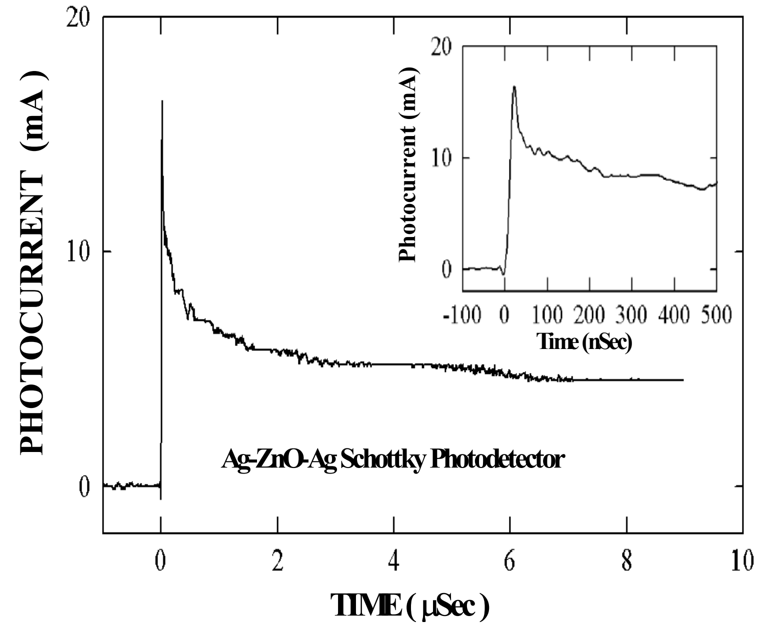
- Wide and direct band gap (3.3eV)
- E_g tunable from 3.3 to 5.8 eV by alloying ZnO with MgO to form $Mg_xZn_{1-x}O$.
- Large photoresponse
- High photoconductivity

Challenges:

- High quality expitaxial film growth of ZnO and $Mg_xZn_{1-x}O$.
- Low response speed due to poor crystalline-quality and impurities.

Photocurrent vs. Response Time of a Photoconductive and Schottky Photodetector





A.Photocurrent vs. Response Time of a Photoconductive Photodetector

Rise Time: 1μs

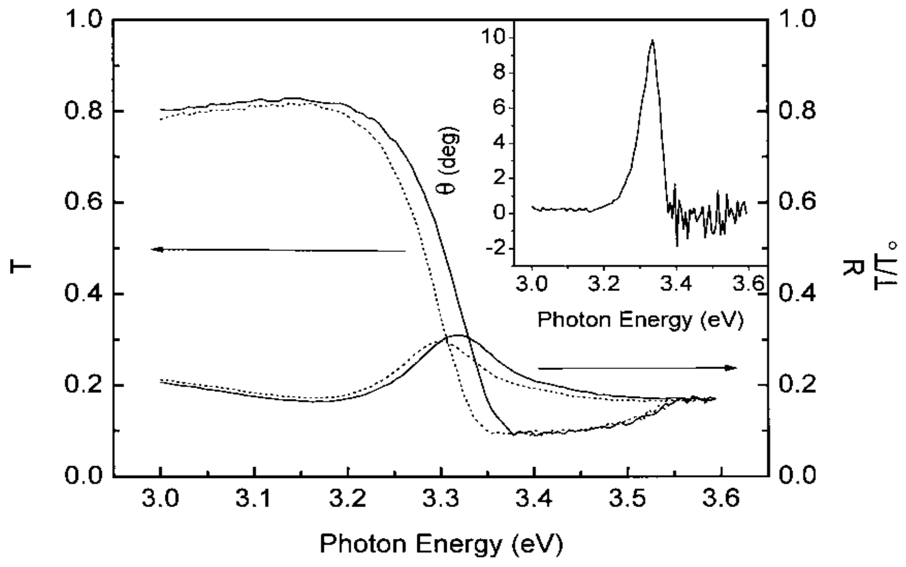
Fall Time: 1.5μs

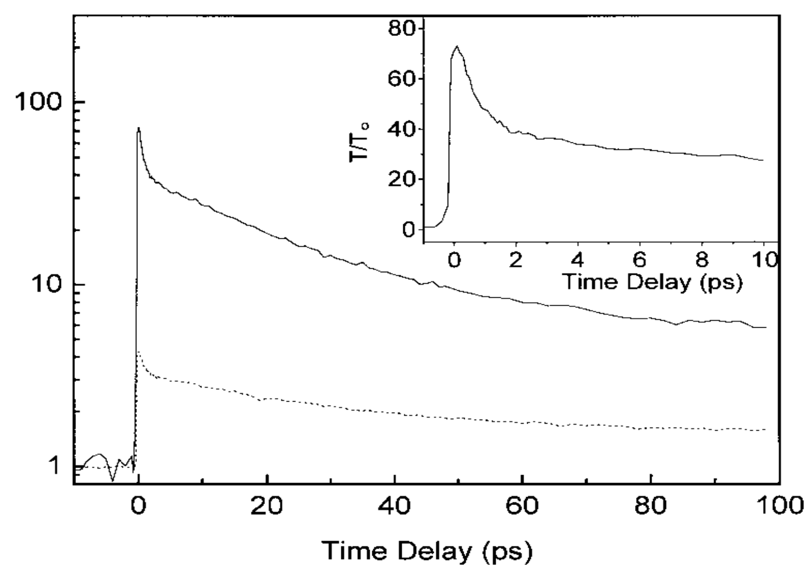
B.Photocurrent vs. Response Time of a Schottky Photodetector

Rise Time: 12ns

Fall Time: 50ns

ZnO Optically Addressed UV Modulator





- Contrast ratio 70:1
- Dynamic rotation 12°
- FWHM less than 3ps
- Electrically addressed ZnO UV modulator in progress

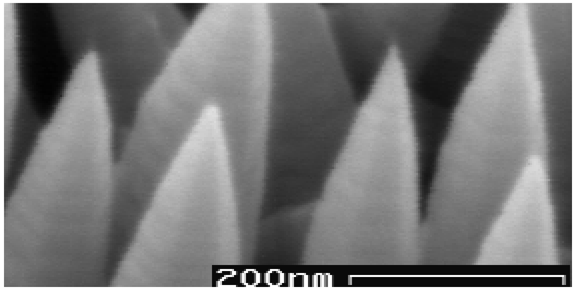
Novel MITSAW Device

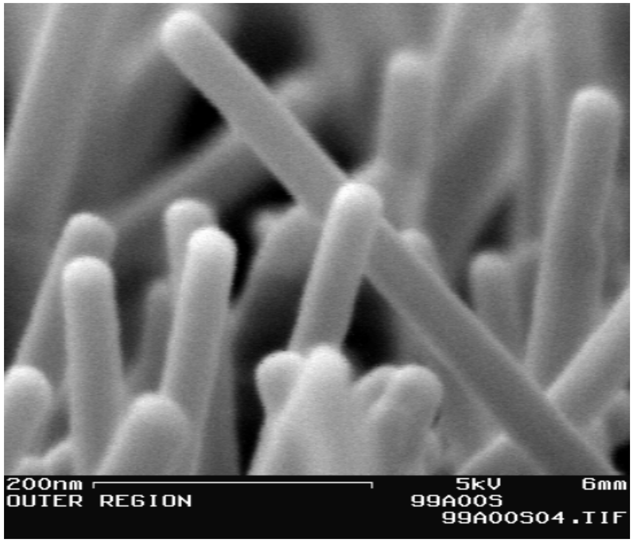
- Aims to develop a ZnO based monolithically integrated tunable surface acoustic wave (MITSAW) chip which integrates acoustic, optical and electrical process' in one material system to create tunable phenomena
- Uses ZnO piezoelectric films and ZnO/ $Mg_xZn_{1-x}O$ heterostructures deposited on R-plane sapphire (R-Al_2O_3).
- Interaction between the electrons in the ZnO/ $Mg_xZn_{1-x}O$ QW and the E field of the propagating SAW is used to tune velocity.
- ZnO/R-Al_2O_3 system for high K^2, high v_{SAW}.
- $Mg_xZn_{1-x}O$/ZnO heterostructure/QW for 2D electron confinement.
- Applications: VCO, adaptive and tunable filters, 0-power wireless sensors, multi-mode chemical/biochemical sensors

ZnO Nanotips for Biosensing

The sharp nanotips can be used as binding sites for biomolecules such as DNA, lipoproteins (LDL), etc.

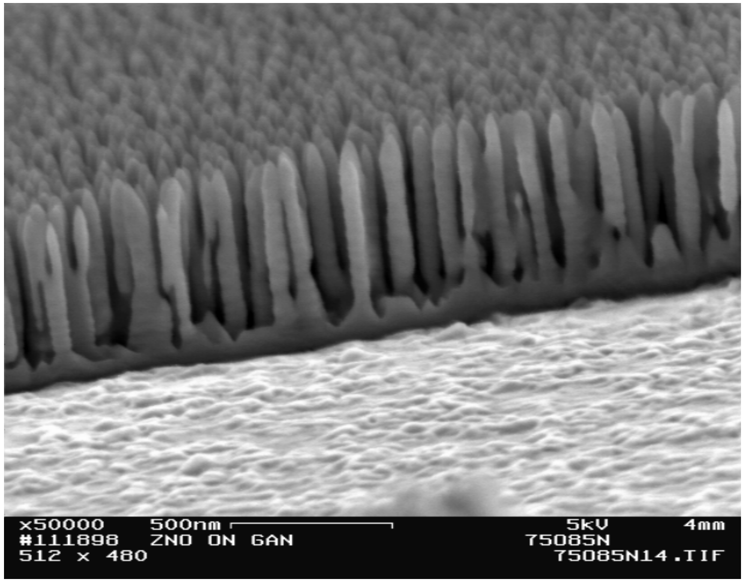
On Al_2O_3=>





<= On Si

on GaN =>



Conclusions

1. $ZnO/Mg_xZn_{1-x}O$ is a promising sensing material system:
   – Multifunctionality
   – Tunability
   – Integratability
   – Manufacturability (low cost)
2. ZnO based sensor devices have broad applications:
   – UV sensors (solar blind)
   – Biosensors (SAW, BAW, dual mode)
   – Wireless passive sensors (zero power consumption)
   – Magnetic sensors
   – High energy particle sensors
   – MITSAW multifunctional sensors