Pushing the ultimate CMOS and beyond

High k dielectrics on high carrier mobility semiconductors for ultimate CMOS - accomplishments and the remaining challenges

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Nano National Program

academic excellence

NSRRC; NDL; NTU
NTHU; NCU; NSYSU
Univ. Illinois at Urbana
Yale Univ.; Purdue Univ.
Rutgers Univ.
Bell Labs; IBM; Intel; IMEC

Supports and collaboration

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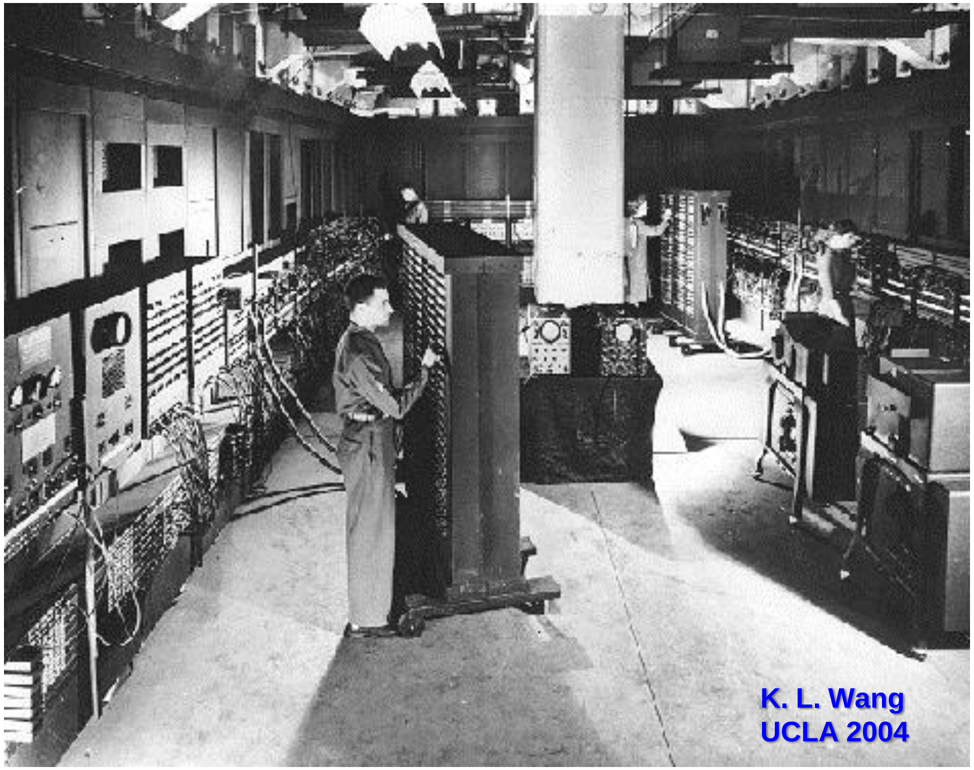
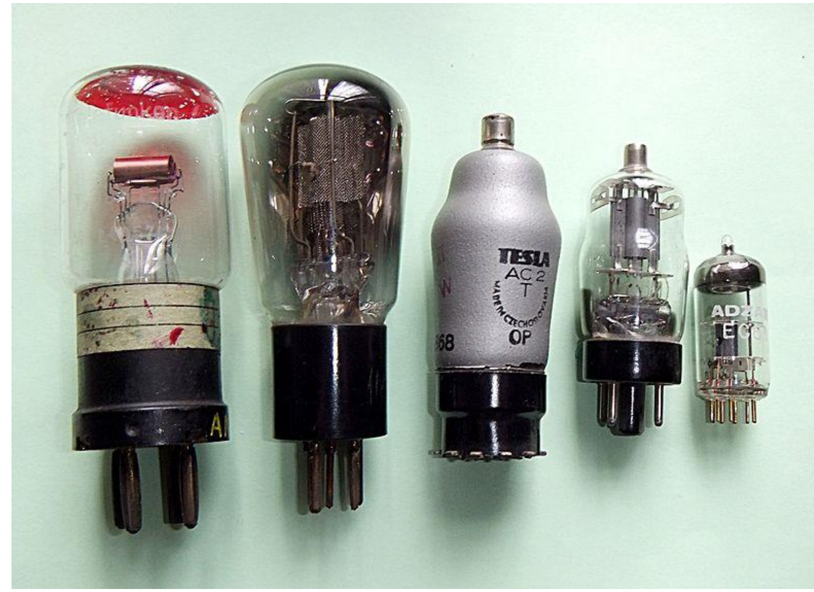
I think that there's a world market for about 5 computers.

-Thomas J. Watson, Sr., IBM Chairman of the Board, 1946



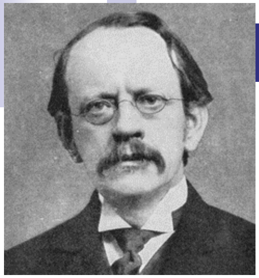
The ENIAC (Electronic Numerical Integrator and Computer) **machine occupied a room 30 x 50 ft.** **(van Pelt Library, U Penn)**



Triodes as they evolved over 40 years of tube manufacture, from the RE16 in **1918 to a 1960s** era miniature tube

The scaling of CMOS is much more aggressive!

In 1946, a group of scientists and engineers at the U. Penn.'s Moore School of Electrical Engineering quietly inaugurated a revolutionary way of managing information. It gave rise to the modern computer industry and would eventually transform people's lives to a degree that even its inventors could not have imagined.



1897 J. J. Thomson discovery of electron - using properties of cathode rays, electron charges

The cathode ray tube (CRT) is a vacuum tube

What next?

Transistor

Quantum Mechanics

Spin!!!

2007 High k + metal gate on Si f[…]OS; 2010 32 nm, 2012 22 nm, and 2014 15 nm node. InGa[…]aN 2016-2025?

- Mervin Kelly, the th[…]earch at Bell Labs, had predicted the problem and had already […] a solution.
  - Although relay[…]tubes were apparently making all things possible in telephony, he had predicted […] years that the low speed of relays and the short life and high power consumption of tub[…] would eventually limit further progress in telephony and other electronic endeavors.
  - In the summer of 1945, Kelly had established a research group at Bell Labs to focus on the understanding of semiconductors. The group also had a long-term goal of creating a solid-state device that might eventually replace the tube and the relay.

What are the next "Big Innovation(s)"?

In the late 19th, the need to know the essence of electricity was in demand. Therefore, the study in **vacuum technology**, **gas discharge** and **cathode ray** was intensively studied, and as a consequence **electron** was discovered.

- ✓ **Interplay among science (*materials, physics, chemistry*) and technology**

Important scientific and technological topics:

The perfection of ***SiO_2/Si interface*** has been essential for the success of the present CMOS.

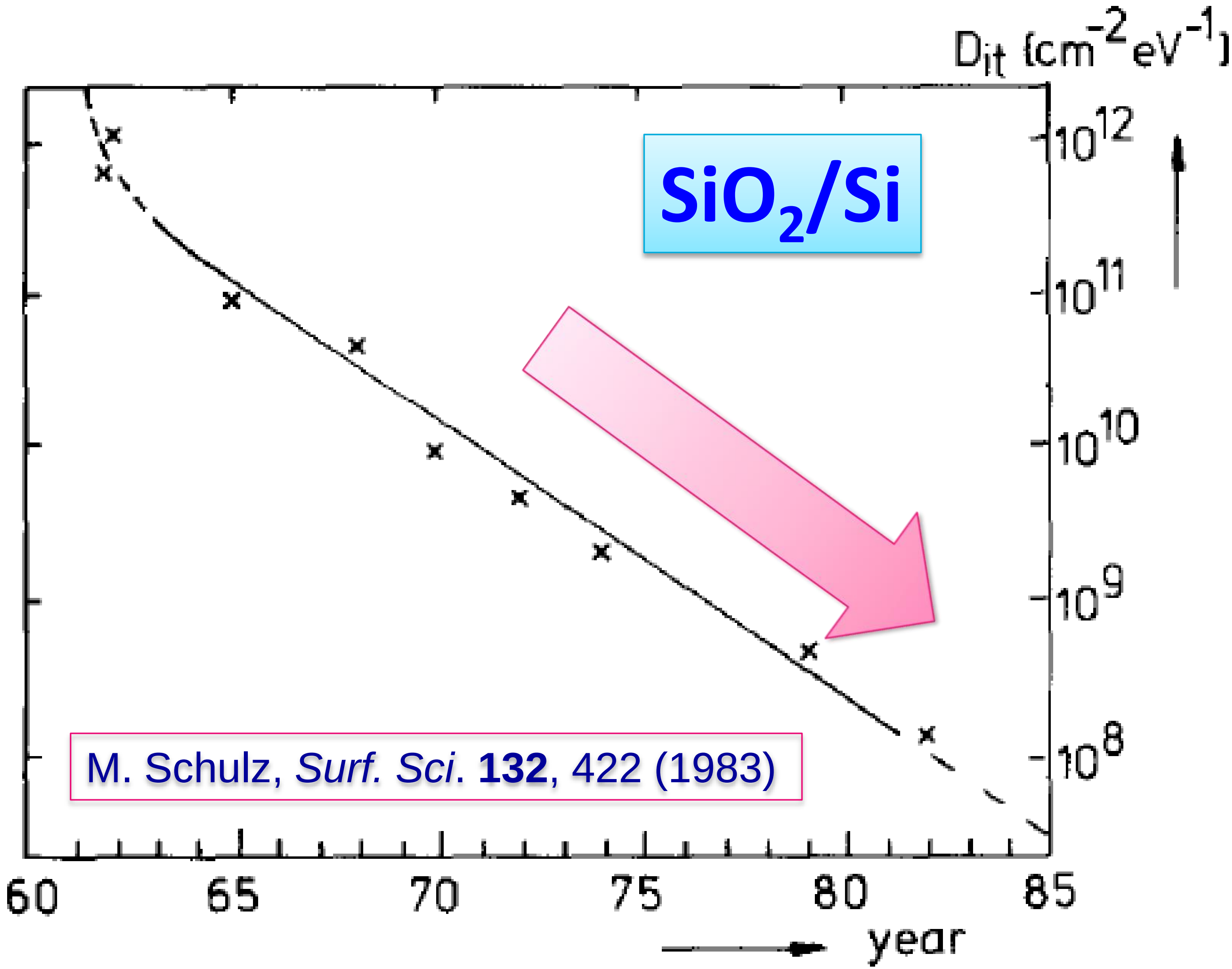
- ***History, Challenges, Opportunities, and Accomplishments***

Fundamental requirements for high κ's + metal gates on InGaAs (or any channels) for ultimate CMOS

- ✓ **Ge MOS**

- ✓ EOT < 0.6 nm (every atom counts!)
- ✓ Interfacial density of states $D_{it} \leq 10^{11}$ cm^{-2} eV^{-1}
- ✓ Self-aligned process
  - ✓ High-temperature thermodynamic stability
- ✓ Low parasitic
  - ✓ Ohmic contacts (Schottky barrier heights) and sheet resistance
- ✓ Integration with Si

SiO_2/Si - from the past to the present



Background leading to unpin surface Fermi level in III-V compound semiconductors at Bell Labs

- Late 1980s to early 1990s, problems in then AT&T's pump lasers (980 nm) for undersea optical fiber cable (trans-Atlantic)
- Semiconductor facet (HR, AR) coating
  - Reducing defects between InGaAs (GaAs) and coating dielectrics
- Electronic passivation much more stringent than optical passivation
  - (110) vs (100) of InGaAs (GaAs)
- ***Passivation of the facets***

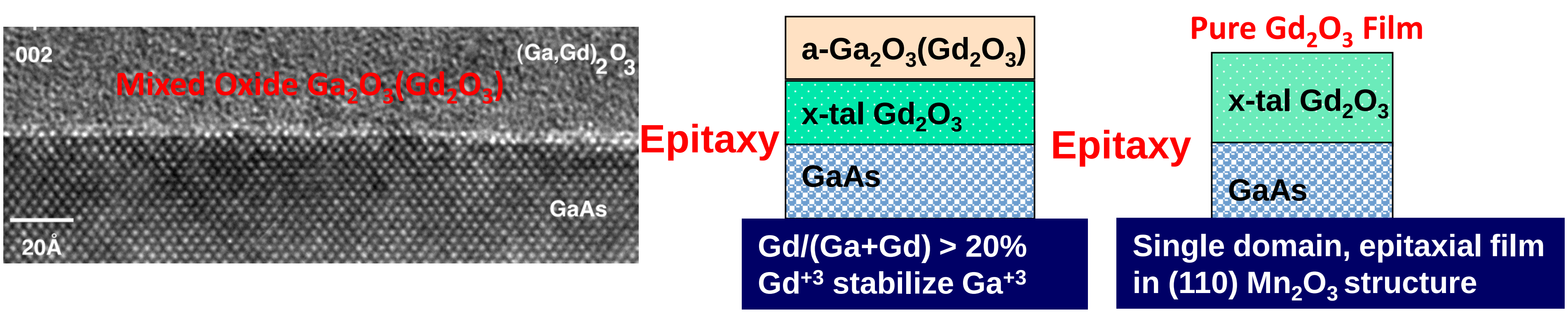
Initial thinking: to attain Ga_2O_3 film for passivation

High-purity single crystal $Ga_5Gd_3O_{12}$ (GGG) source

→ Gd_2O_3 ionic oxide T_m > 4000K

→ Ga_2O_3 more covalent oxide T_m ~ 2000K

→ Ga_2O_3 evaporated mostly, and formed amorphous Ga_2O_3 film



III-V Surface Passivation

Requirements

thermally and electronically stable at high temperatures of >800 ℃
low leakage currents
low interface trap density (D_{it})
high κ values ⇒ low EOT < 1nm

Early Efforts (1960s - 1990s) reviewed by Hong et al, "Encyclopedia of Electrical and Electronics Eng.", v. 19, p. 87, Ed. Webster, John Wiley & Sons, 1999

- Anodic, thermal, and plasma oxidation of GaAs
- Wet or dry GaAs surface cleaning followed by deposition of various dielectric materials

1st Breakthrough (1994)

- *in-situ* UHV deposited **$Ga_2O_3(Gd_2O_3)$ [GGO]** and **Gd_2O_3** (Bell Labs)

Hong, Kwo et al,
- JVST (1996);
- Science (1999)
- APL (1999)

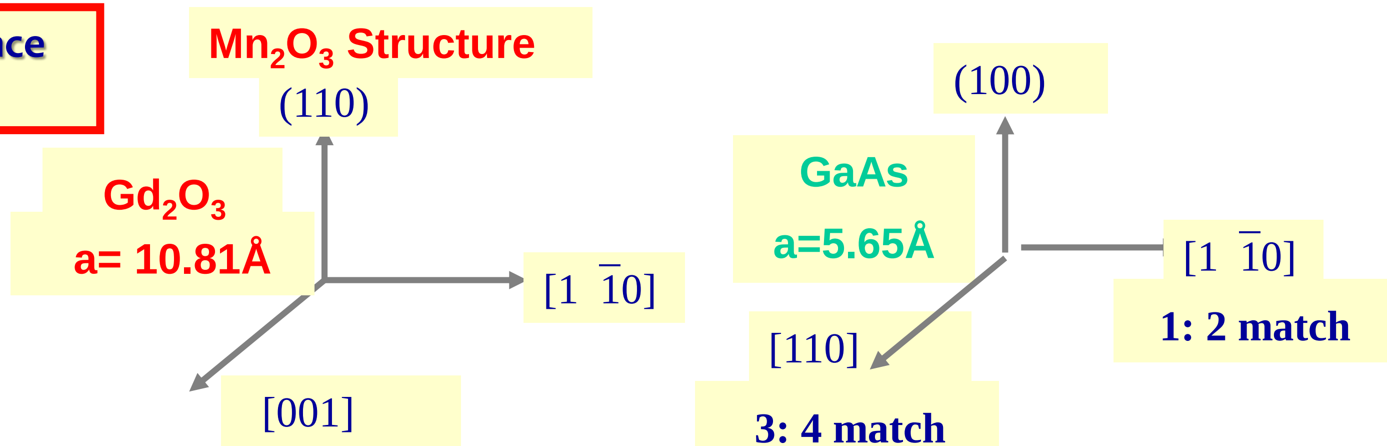
Recent Demonstrations

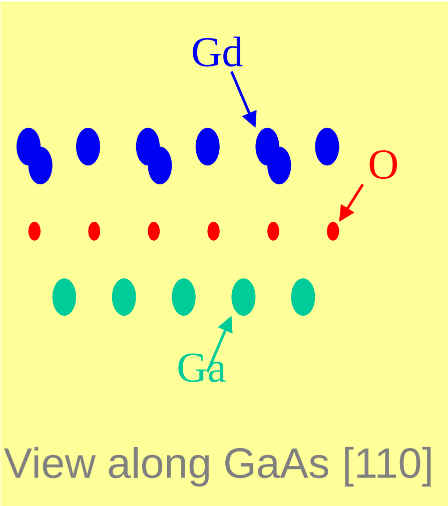
- *in-situ* UHV deposited high-κ's (NTU/NTHU, Freescale/U. Glasgow, IMEC, UT-Dallas …)
- *ex-situ* ALD high-κ's (Agere, Purdue U., NTU/NTHU, Intel, IBM, IMEC, UCSB…)
- a-Si or Ge interfacial passivation layers (IPLs)+ high-κ's

  (IBM, UT-Dallas, UT-Austin, NUS, U. Albany-SUNY/Intel/SEMATECH …)
- *in-situ* ALD high-κ's (NTU/NTHU, UTD)

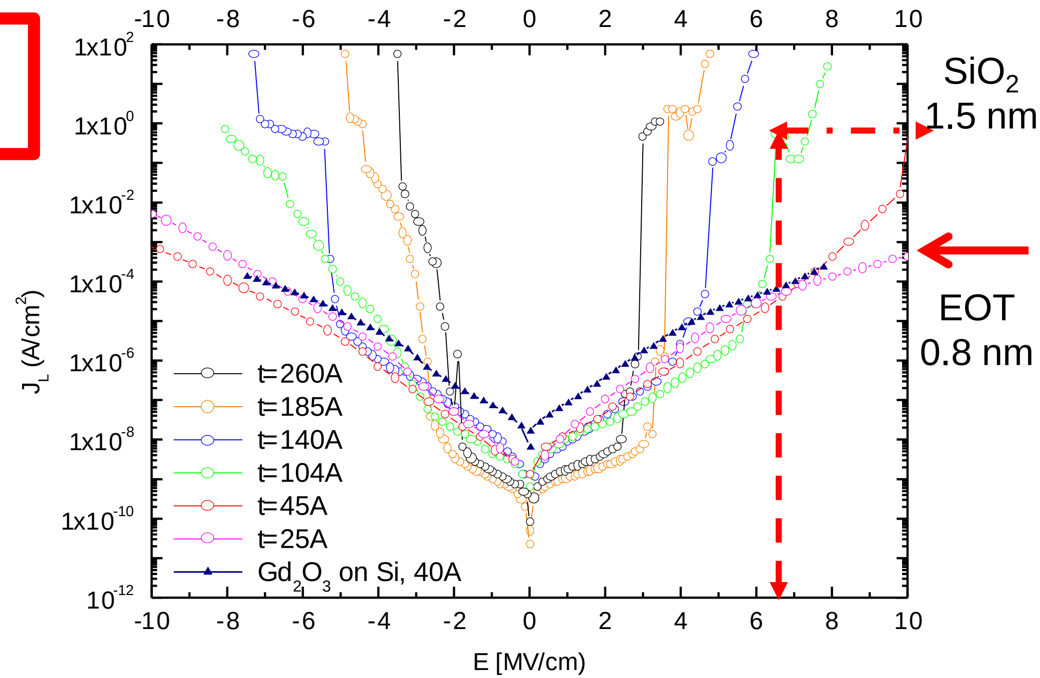
Pioneer Work : Single Crystal Gd_2O_3 Films on GaAs

M. Hong, J. Kwo et al, Science 283, p.1897, 1999

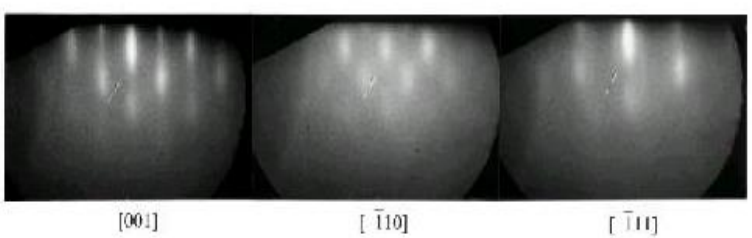




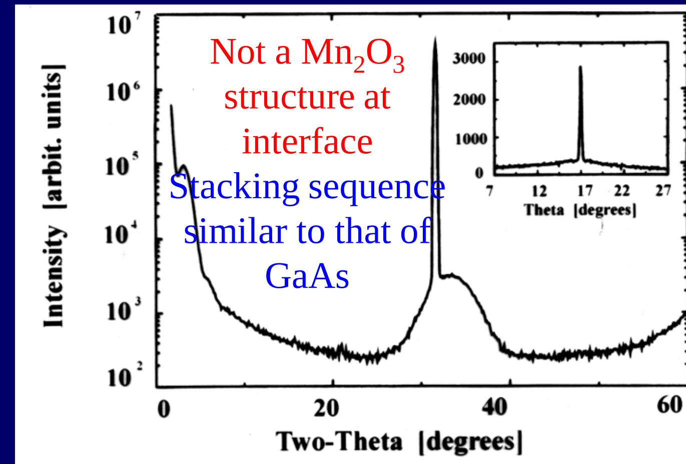
Low D_{it}'s and low J_L

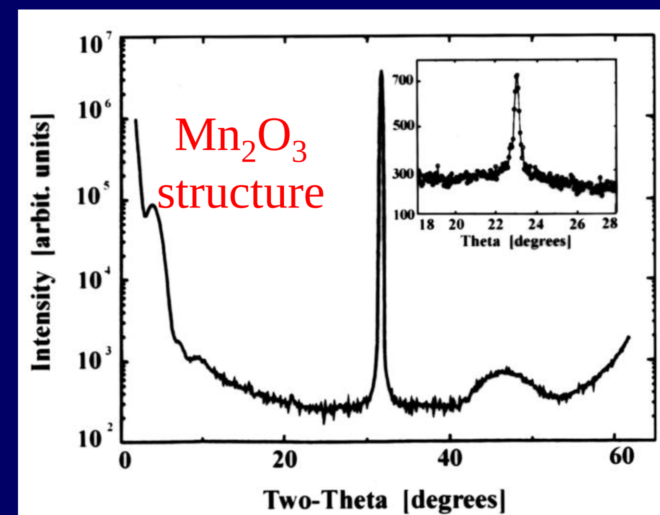


Gd_2O_3 (110) 25Å



Single crystal Gd_2O_3 on GaAs - Epitaxial interfacial structure

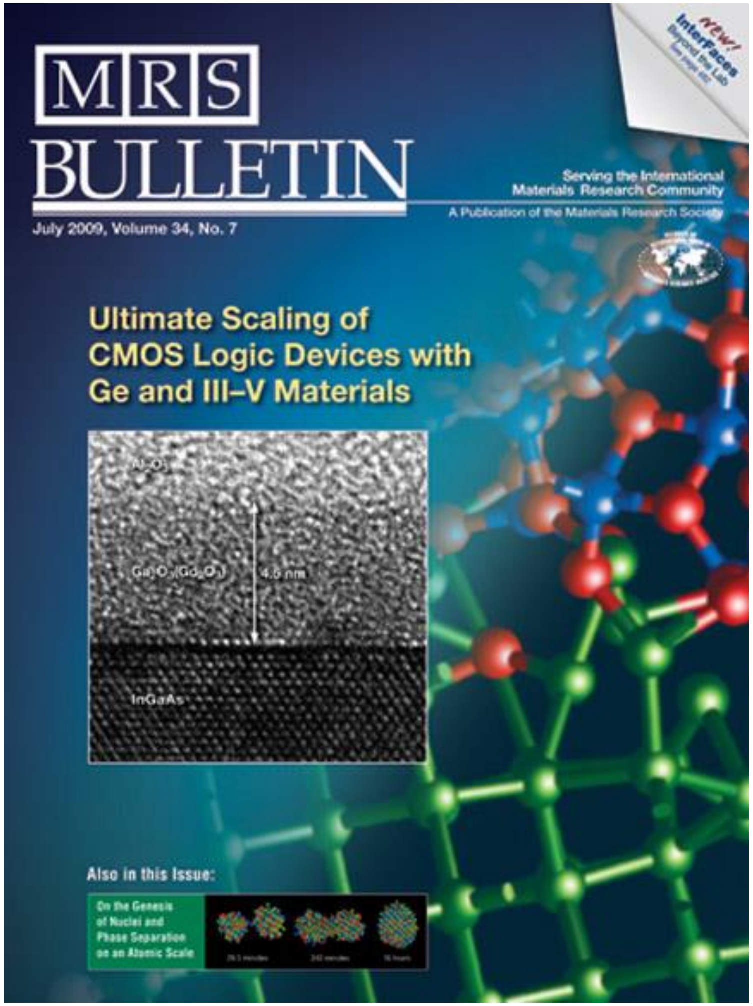


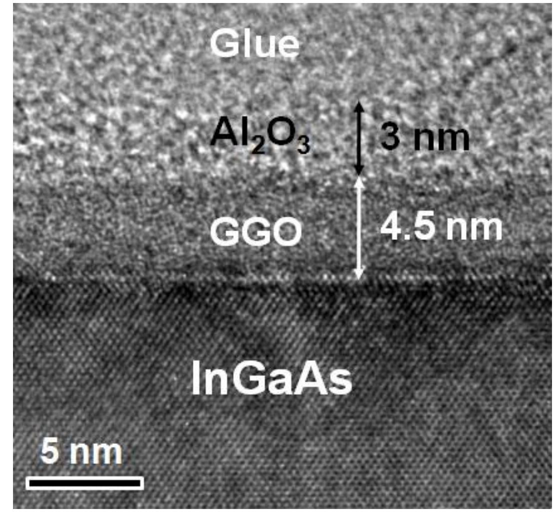


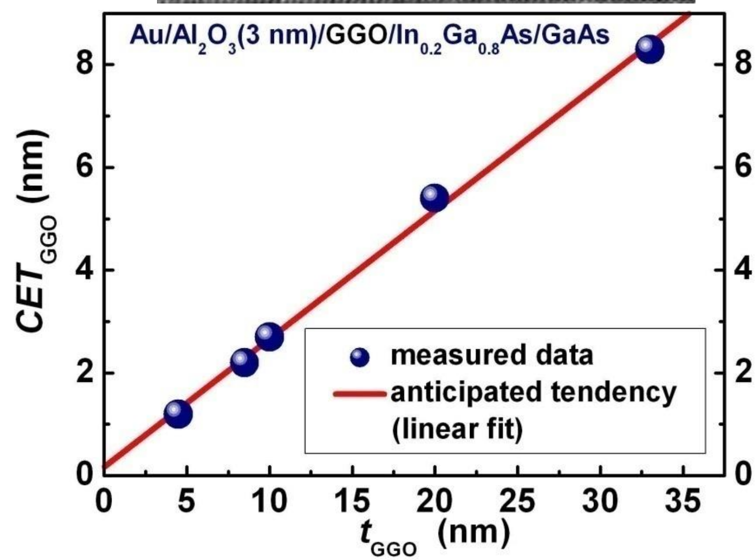
- "New Phase Formation of Gd_2O_3 films on GaAs (100)", J. Vac. Sci. Technol. B 19, 1434 (2001).
- " Direct atomic structure determination of epitaxially grown films: Gd_2O_3 on GaAs(100) " PRB 66, 205311 (2002)
- A new X-ray method for the direct determination of epitaxial structures, coherent Bragg rod analysis (COBRA)

→ Nature – Materials 2002 Oct issue cover paper

MRS Bulletin, July 2009



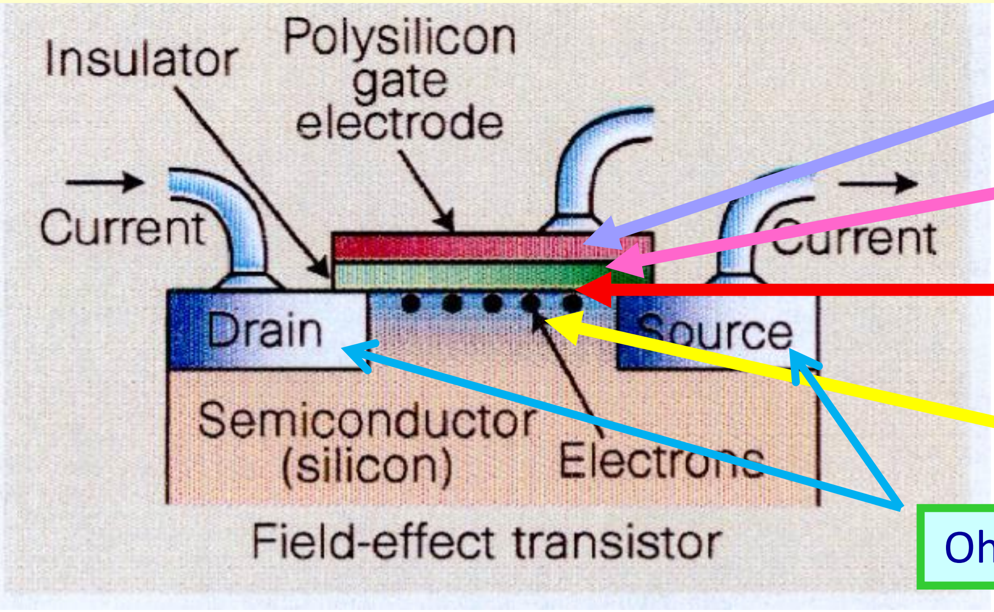




Cover Image & Theme Article – "*InGaAs Metal Oxide Semiconductor Devices with $Ga_2O_3(Gd_2O_3)$ High-κ Dielectrics for Science and Technology beyond Si CMOS*", M. Hong, J. Kwo, T. D. Lin, and M. L. Huang, MRS Bulletin **34**, 514 July 2009.

Device Scaling – Beyond Si CMOS:
high κ, metal gates, and high carrier mobility channel

1960 Kahng and Atalla, Bell Labs First MOSFET



Integration of IIIV, Ge, GaN with Si

Moore's Law:
The number of transistors per square inch doubles every 18 months

Shorter gate length L
Thinner gate dielectrics t_{ox}

Driving force :
High speed
Low power consumption
High package density

Pioneering work of (In)GaAs MOSFET's using $Ga_2O_3(Gd_2O_3)$ at Bell Labs

- 1994
  - novel oxide $Ga_2O_3(Gd_2O_3)$ to effectively passivate GaAs surfaces
- 1995
  - establishment of accumulation and inversion in p- and n-channels in $Ga_2O_3(Gd_2O_3)$-GaAs MOS diodes with a low D_{it} of 2-3 x 10^{10} cm^{-2} eV^{-1} (IEDM)
- 1996
  - first e-mode GaAs MOSFETs in p- and n-channels with inversion (IEDM)
  - Thermodynamically stable
- 1997
  - First inversion-channel n-InGaAs/InP MOSFET with g_m= 190 mS/mm, Id = 350 mA/mm, and mobility of 470 cm^2/Vs (DRC, EDL)
- 1998
  - d-mode GaAs MOSFETs with negligible drain current drift and hysteresis (IEDM)
  - inversion-channel GaAs MOSFETs with improved drain current (over 100 times)
  - Dense, uniform microstructures; smooth, atomically sharp interface; low leakage currents
- 1999
  - GaAs power MOSFET
  - Single-crystal, single-domain Gd_2O_3 epitaxially grown on GaAs
- 2000
  - demonstration of GaAs CMOS inverter

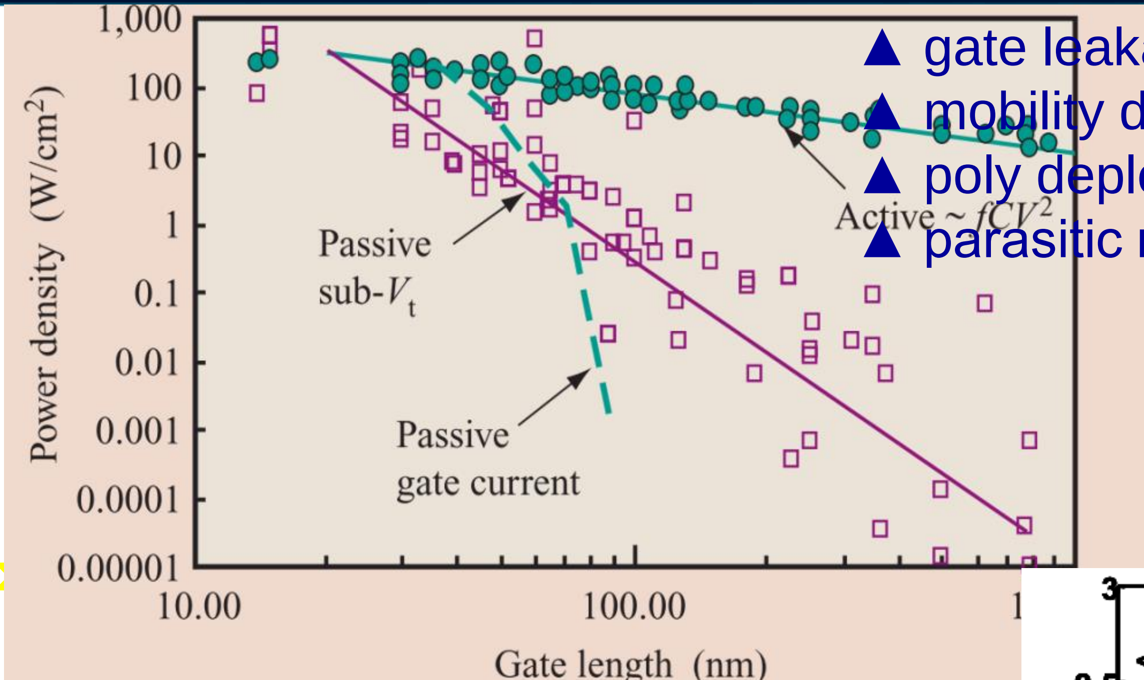
Our major achievements in 2003-2014 in Taiwan

- High κ/GaAs(001) (111)A; $In_{0.2}Ga_{0.8}As$
  - MBE-, MBD- and ALD-oxides: rare-earth oxides, Al_2O_3 and HfO_2
  - Small frequency dispersion for both n- and p-MOSCAPs having symmetrical CVs
  - Low D_{it} with no mid-gap peak
  - New phase of Y-doped HfO_2 (k = 32)
  - Thermodynamically stable to 950C
  - Low EOT (CET) with novel phase transformation from hexagonal to monoclinic
  - Record-high device performances in inversion-channel and D-mode MOSFETs
- High κ/$In_{0.53}Ga_{0.47}As$
  - MBE- and ALD-oxides: rare-earth oxides, Al_2O_3 and HfO_2
    - breaking the myth that tetra-valence HfO_2 could not unpin III-V InGaAs
  - Thermodynamically stable to 850C
  - Excellent CVs
  - Record-high device performances in inversion-channel MOSFET
- High κ/Ge with no GeO_2 nor IPLs
  - Excellent CVs with low D_{it} below 10^{11} cm^{-2} eV^{-1} (via charge pumping and conductance method)
  - Excellent device performance in MOSFETs
  - Thermodynamically stable

Our major achievements in 2003-2014

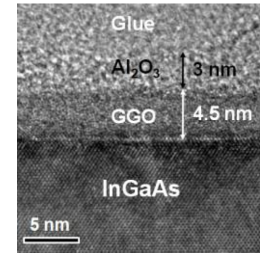
- High k/GaN
  - Ultra-low CET been achieved with single crystal hexagonal rare-earth oxide on GaN
  - ALD-oxides
  - Small dispersion in accumulation of CVs with small hysteresis
  - First inversion-channel MOSFET with decent electrical characteristics
  - Record high device performance in D-mode (accumulation) MOSFETs
- High k/GaSb
  - Interface free of SbOx
  - Attainment of decent C-V, J-E (~10^{-8}A/cm^2), and small C-V hysteresis (~0.03V) characteristics
  - Thermally stable up to 500^{o}C
  - Record high device performance in inversion-channel GaSb MOSFETs
- Probing the "true" surface and interface
  - Surface structures of (In)GaAs(001) and (111)A surfaces
  - Atom-by-atom interaction in ALD-oxides on (In)GaAs
- Single crystal oxides on Si
  - Perfection of oxide crystallinity
  - Template for ZnO and GaN overgrowth
- Spintronics
  - Spin pumping from ferromagnetic Fe_3Si into n- and p-GaAs
  - Record high inverse spin Hall voltage

Why high-κ/III-V's?



- ▲ gate leakage
- ▲ mobility degradation
- ▲ poly depletion
- ▲ parasitic resistance …

III-V

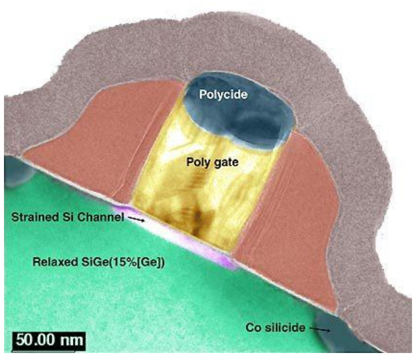


15nm
2014-2015

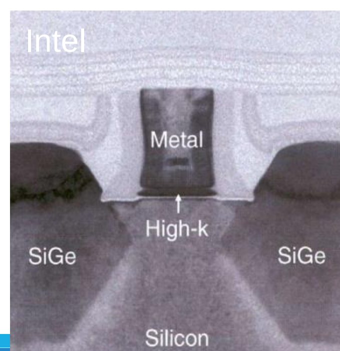
10--7nm
2014 … ?

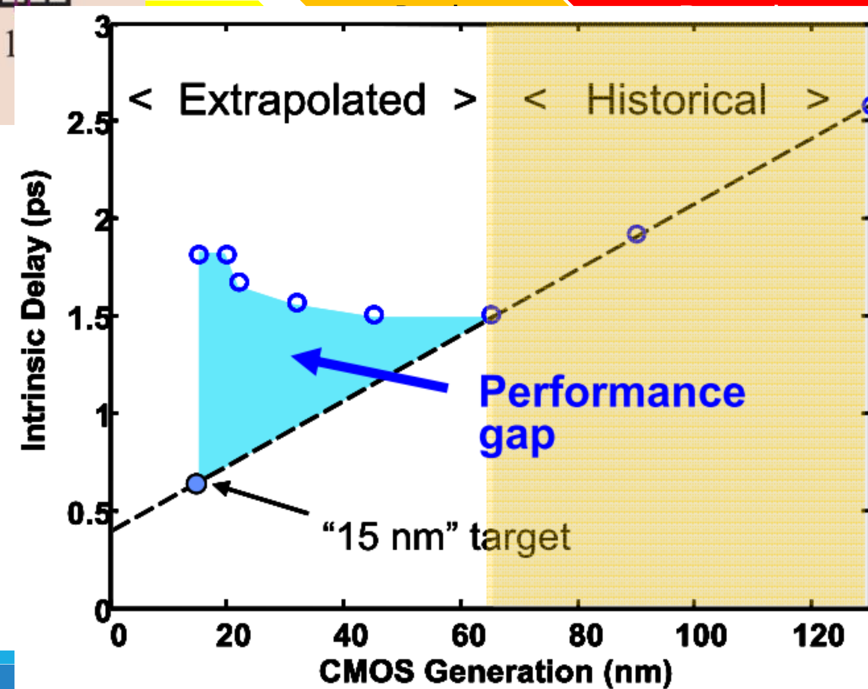
W. Haensch *et al*., IBM J. Res. & Dev. **50,** 339 (2006)

Strained Si

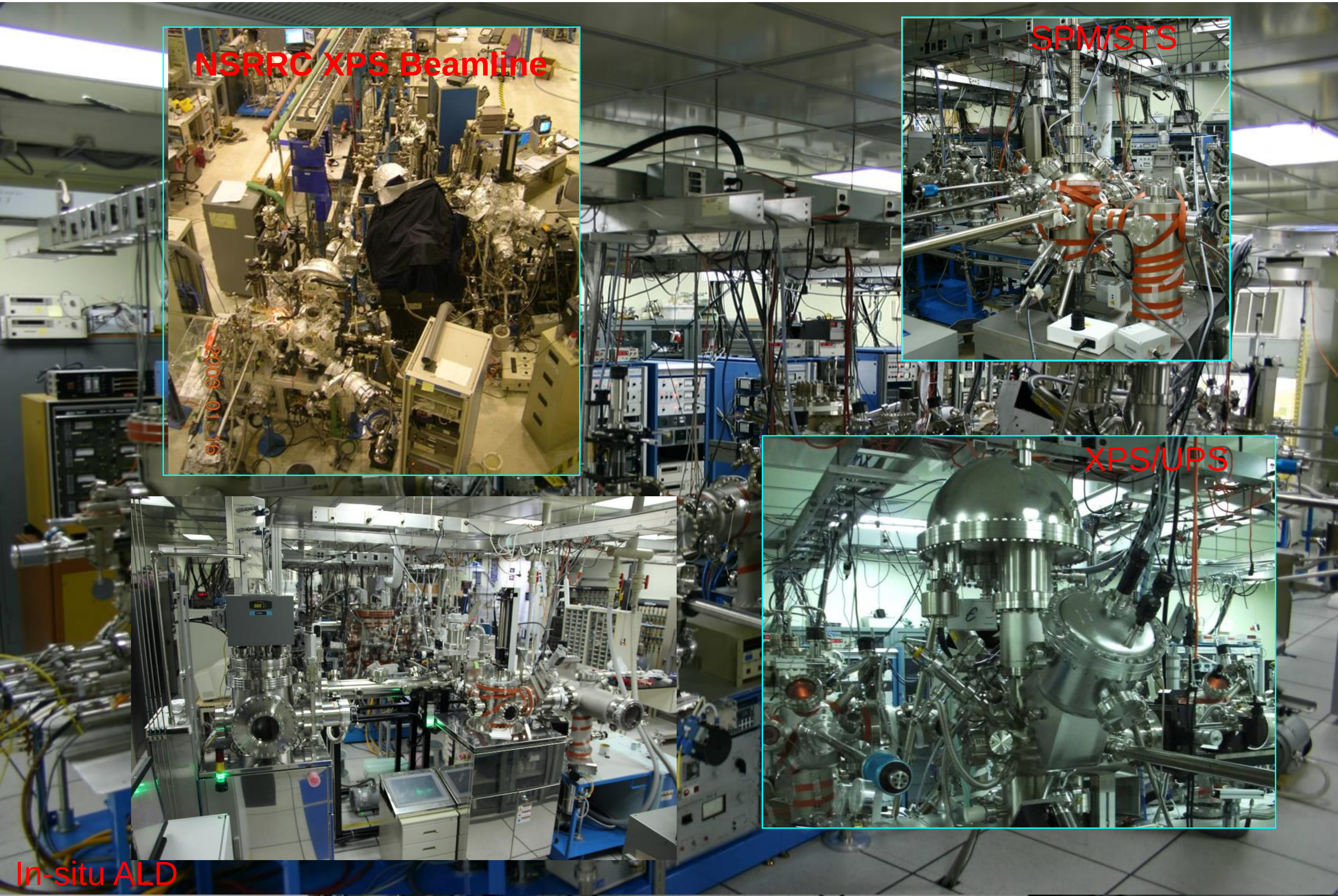


High-κ metal Gate





D. Antoniadis, MIT


NSRRC XPS Beamline
SPM/STS
XPS/UPS
In-situ ALD