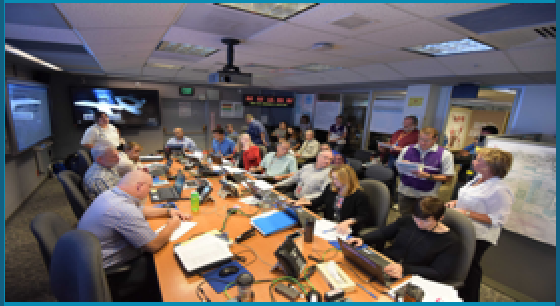
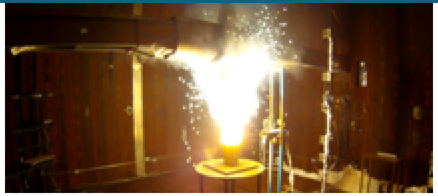
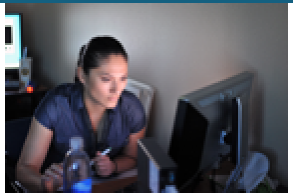
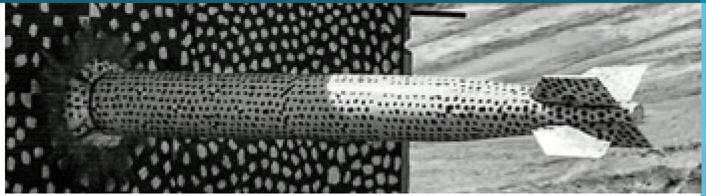
SAND2021-2667C

Room Temperature Operation of Donor-Based Atomically Precise Devices









Jeffrey A. Ivie*, Lisa A. Tracy, Juan P. Mendez, Suzy Gao, Evan M. Anderson, Scott W. Schmucker, DeAnna M. Campbell, David Scrymgeour, Aaron M. Katzenmeyer, Dan R. Ward, Tzu-Ming Lu, Shashank Misra

Sandia National Laboratories, Albuquerque, NM, USA

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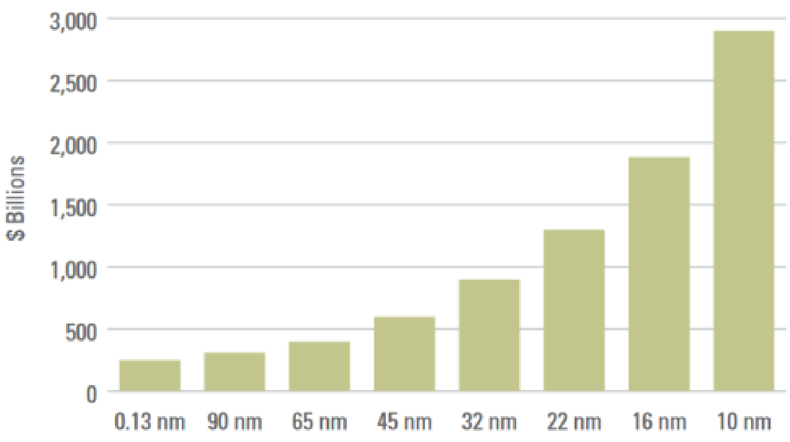
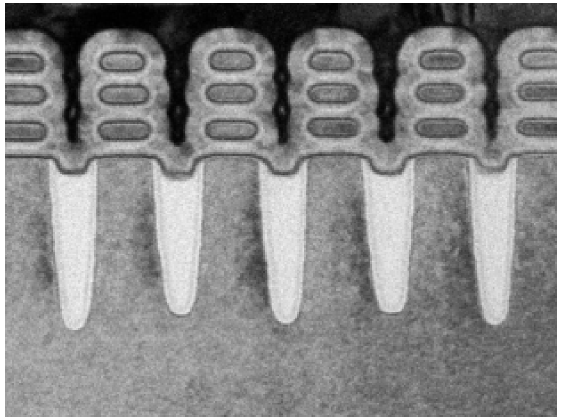
Beyond Conventional CMOS: Nanoscale Devices

Figure 5: Process Technology Development Costs by Node (US$ billions)

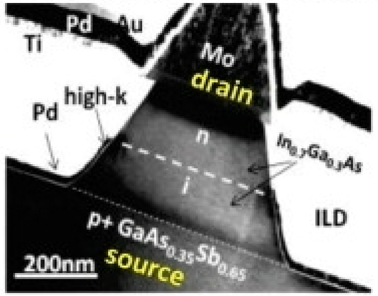


Source: Common Platform Technology Forum 2012 and AlixPartners analysis



Nanosheet -> **Confinement**
Source: IBM

(b) Vertical n-type III-V HTFET cross-section TEM Micrograph



TFET -> **Tunneling**
Tomioka, K. *et. al.*
Nature, **488**, 189 (2012)

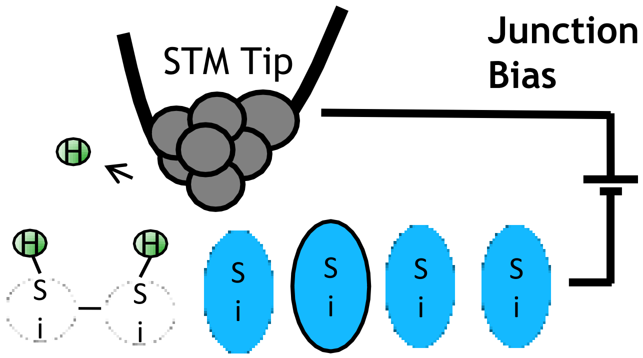
4K-400K temperature studies: >500 nm MOSFET (1980-1990's)

4K-400K Temperature Studies for <10 nm? <u>Missing!</u>

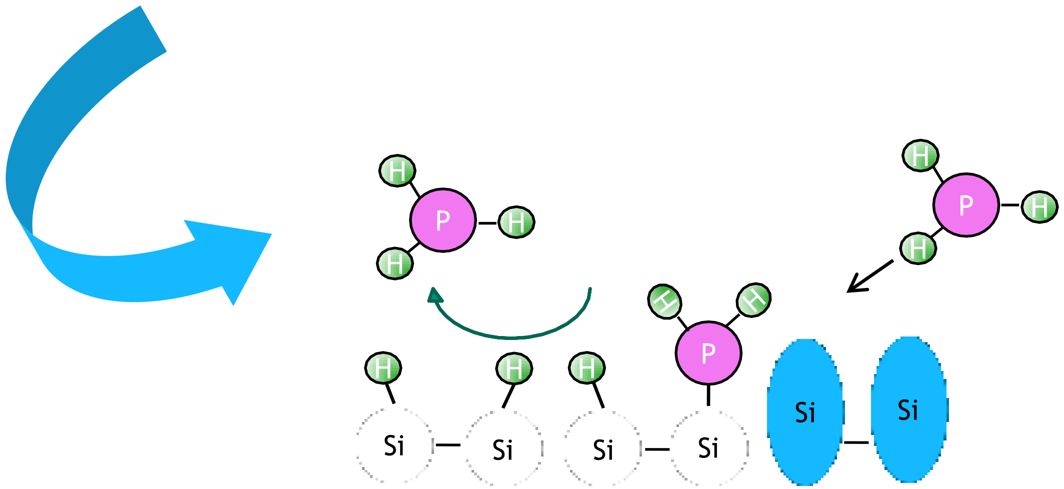
4K Temperature Studies: <10 nm nanoscale devices (Modern)

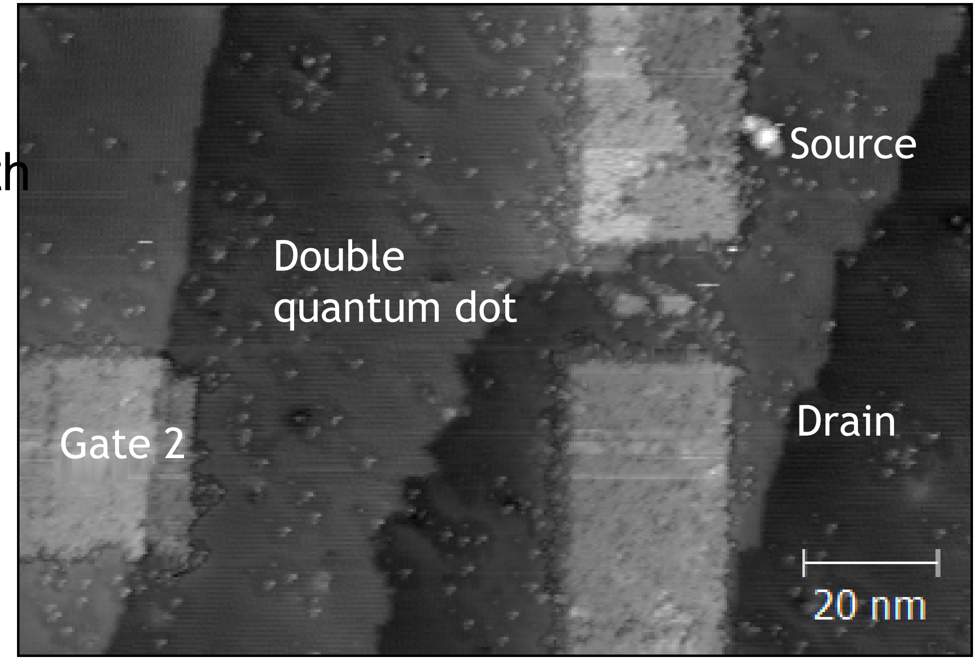
Need for Robust Platform for *Variable* Temperature (4 – 400K) Studies of Quantum Effects in <10 nm devices (Atomic Precision)

Atomic Precision Advanced Manufacturing (APAM): Ultra High Doping



Atomic precision achieved through hydrogen desorption with scanning tunneling microscope (STM)





STM

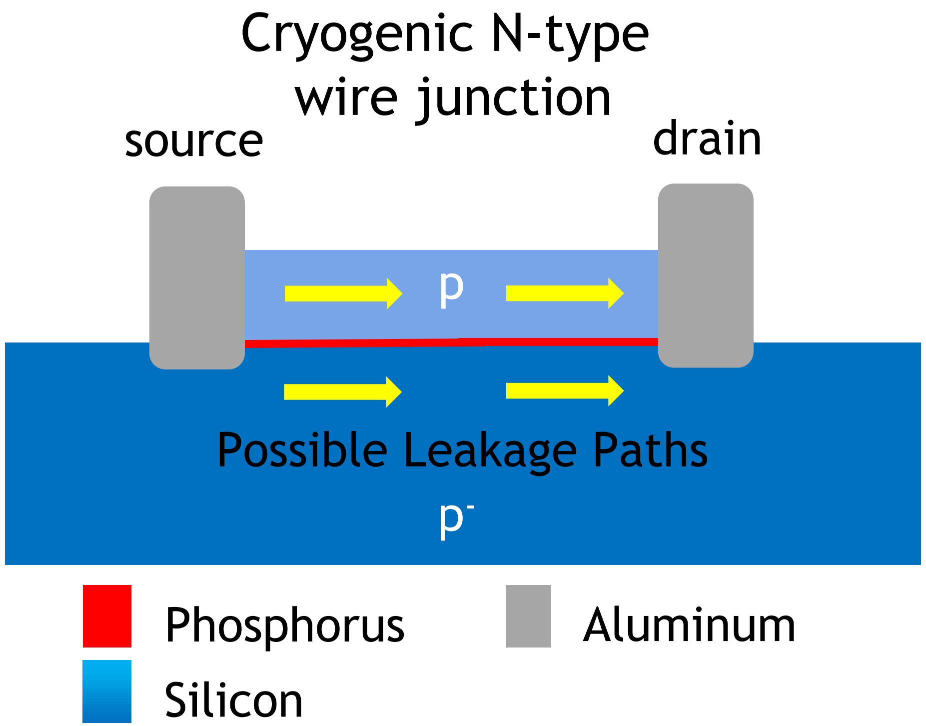
- Expose to PH_3 precursor, which **only** bind to exposed reactive sites
- Generate dopant concentrations **above solubility limit** (~1×10^{20} atoms/cm^3)

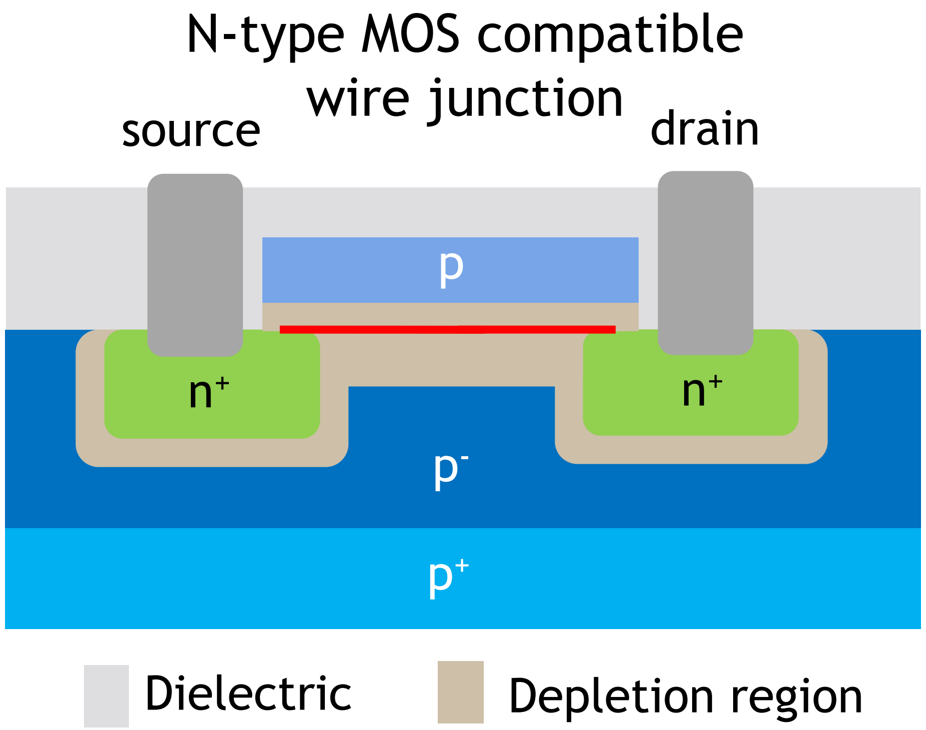
Result: Atomic Precision Quantum Devices

Ward, *et. al. Elec. Dev. Fail. Anal.*, **22**, 1, 4-

APAM + MOS: Need Room Temperature Operation

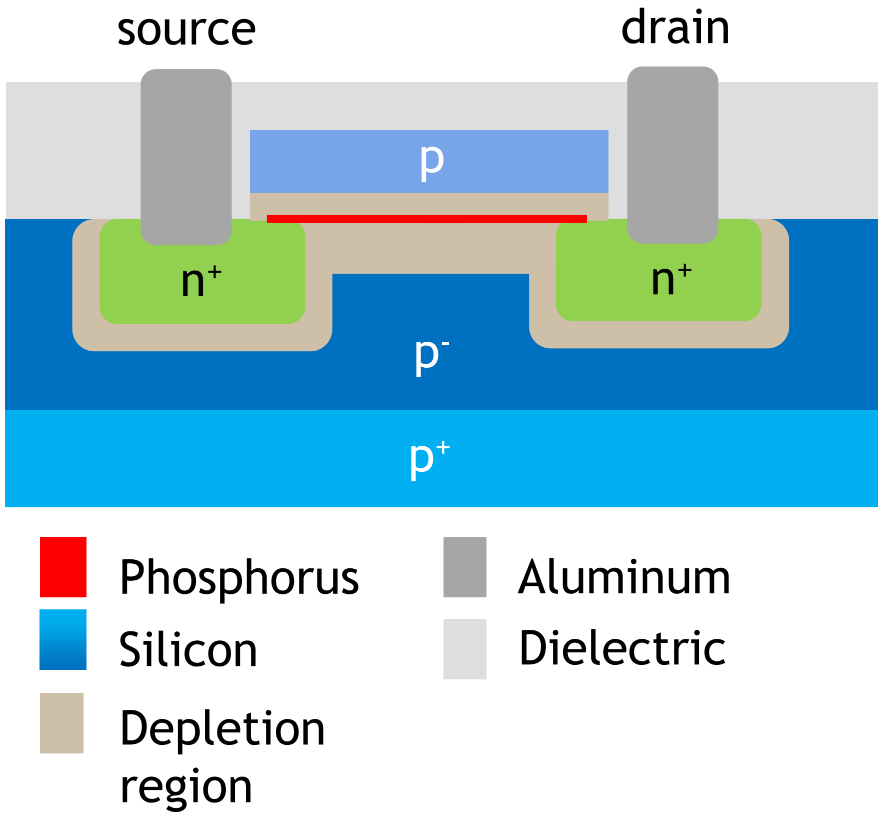
- **Problem:** APAM quantum devices **only** operate at 4K or lower.
  - Leakage currents become major issue at higher T
- **Solution!** Adapt MOS-like doping schemes

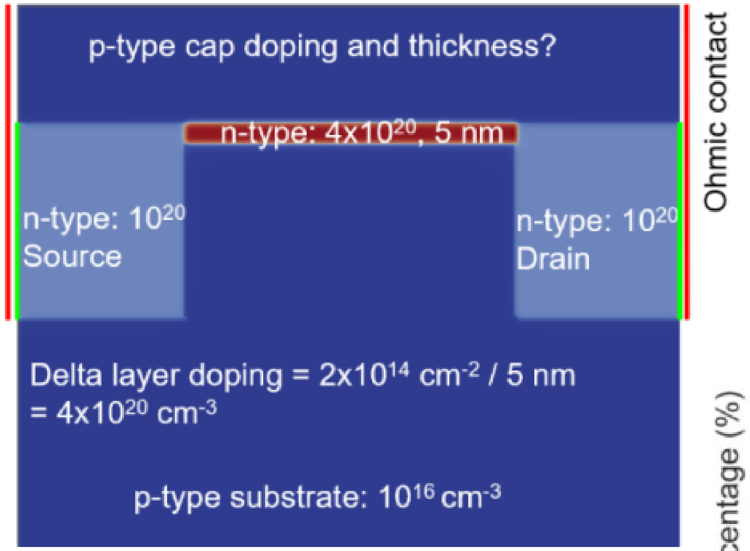




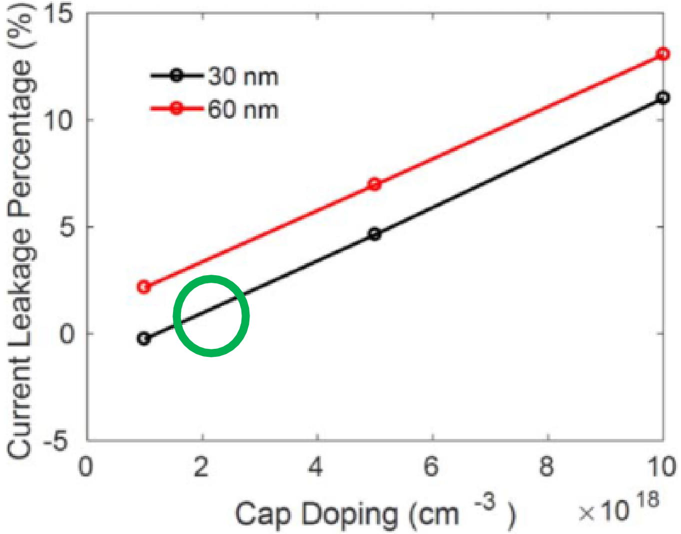
Will the MOS doping scheme minimize leakage?

RT APAM Device Leakage Modeling





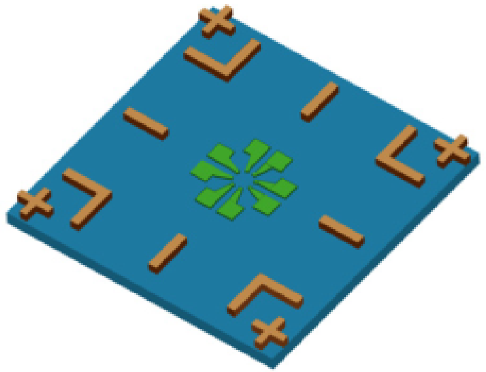
TCAD:
charon.sandia.gov

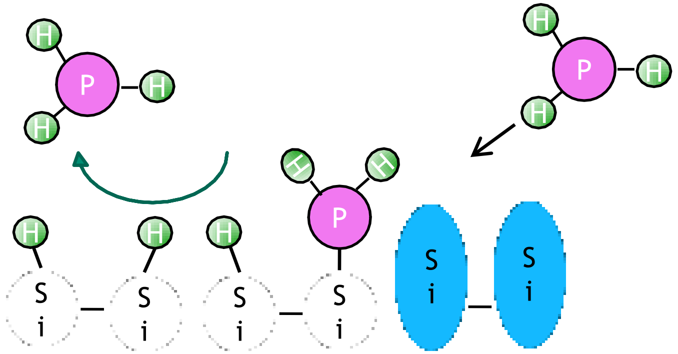


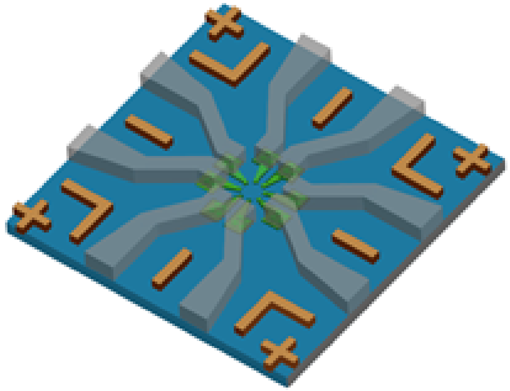
Cap should be depleted according to TCAD simulations
Substrate isolated by dielectric and appropriate doping scheme

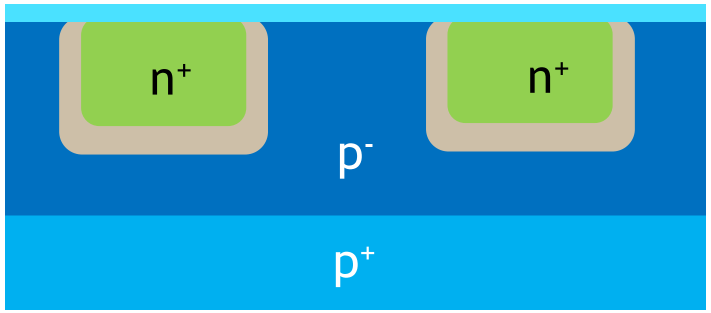
Gao, X *et. al.* *SISPAD*, 2020 (IEEE)

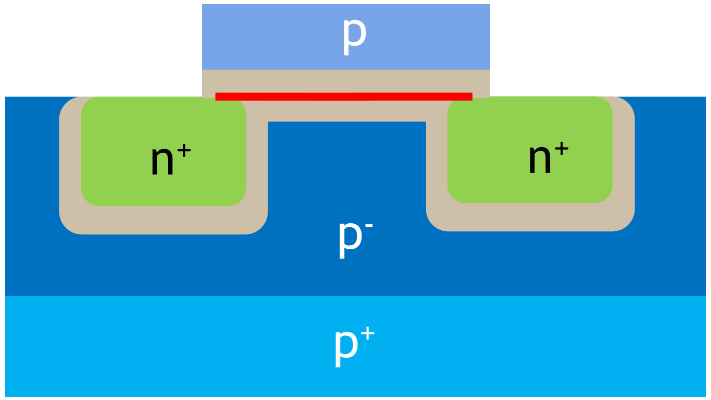
Overview of Fabrication Process

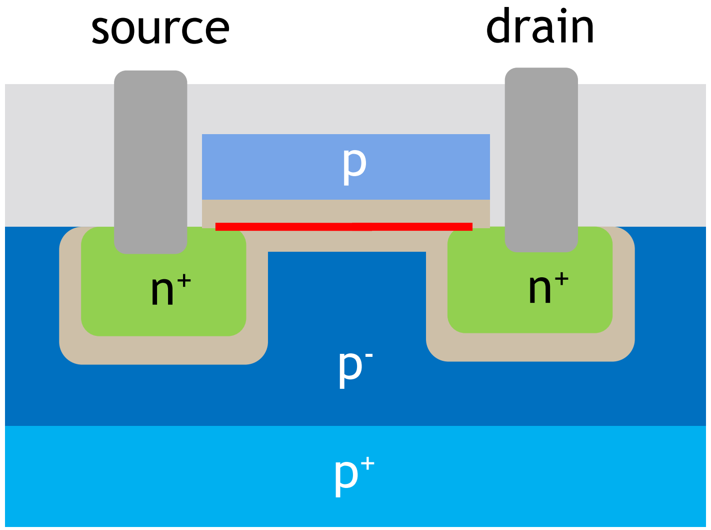












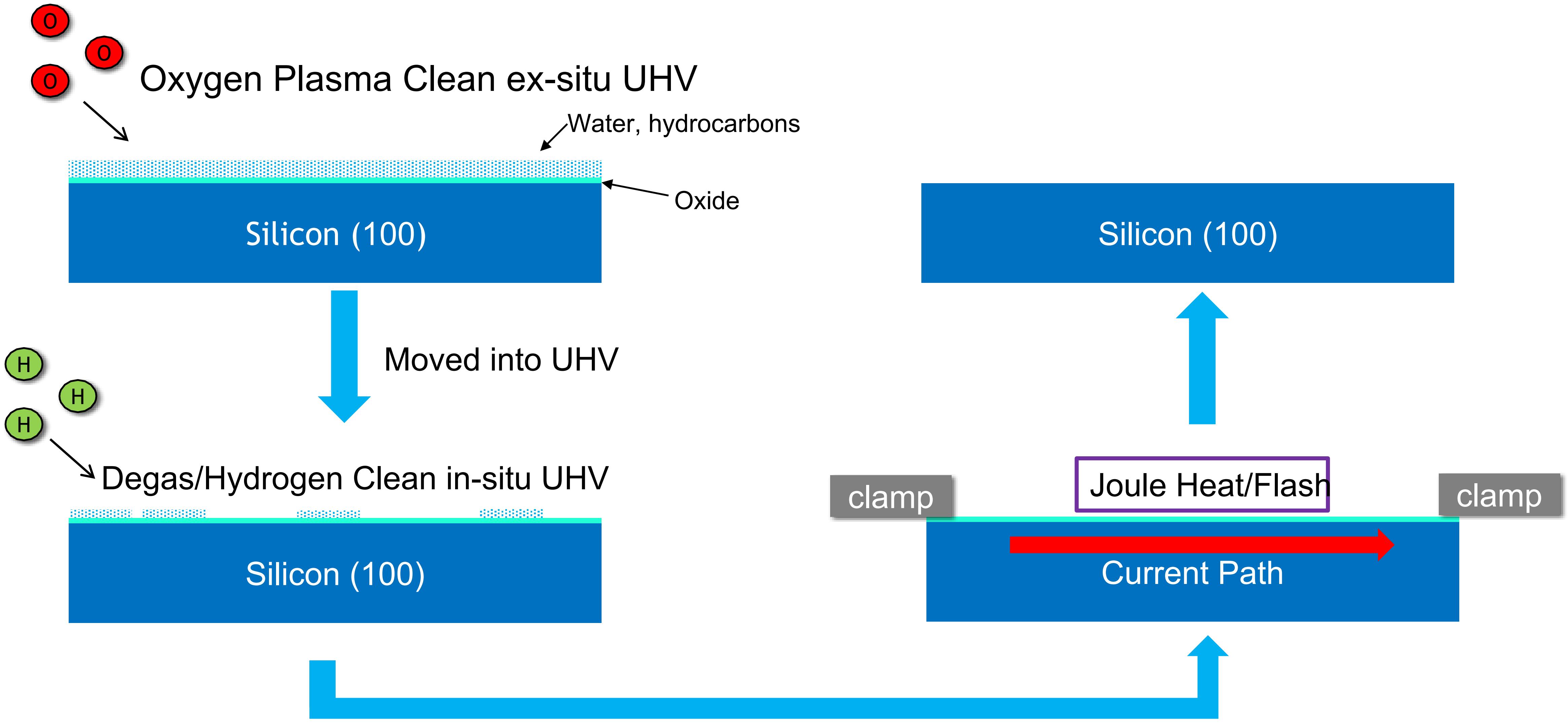
Pre-Processing:
Implants, Markers, protective oxide growth

APAM: δ-layer & capping Si layer growth

Post-Processing:
Dielectric, metal contact placement

Ward, *et. al. Appl. Phys. Lett*, ***111***, 193107 (2017)

Standard APAM Preparation Procedure



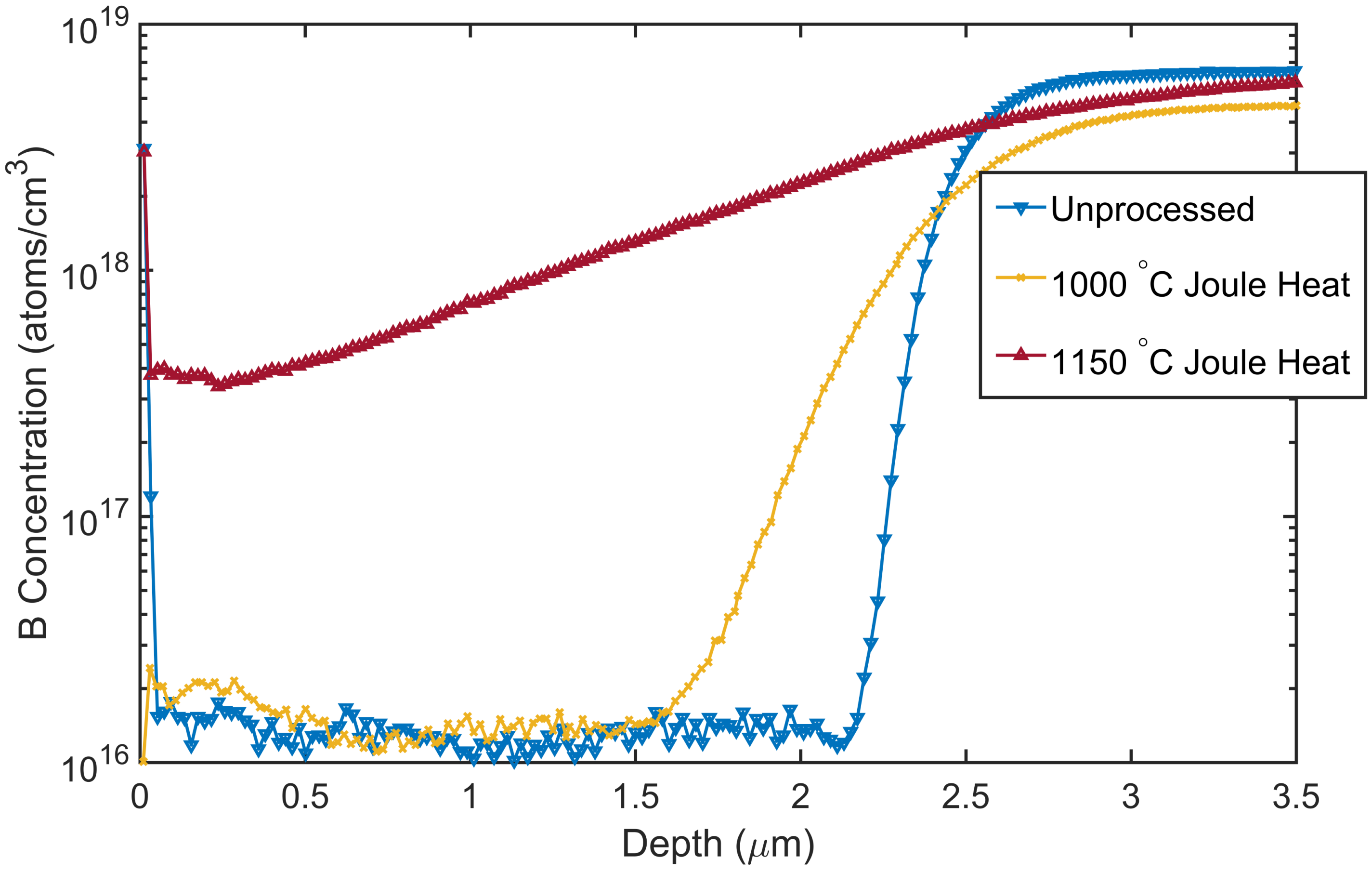
Ward, *et. al. Appl. Phys. Lett*, ***111***, 193107 (2017)
Ward, *et. al. Elec. Dev. Fail. Anal.*, **22**, 1, 4-10 (2020)

Preventing B Diffusion during Joule Heating

- Joule Heat p-/p++ chip for 60 minutes at different temperatures
- SIMS (secondary ion mass spectroscopy) to determine boron concentrations post-Joule heating

Si (100) chip under test

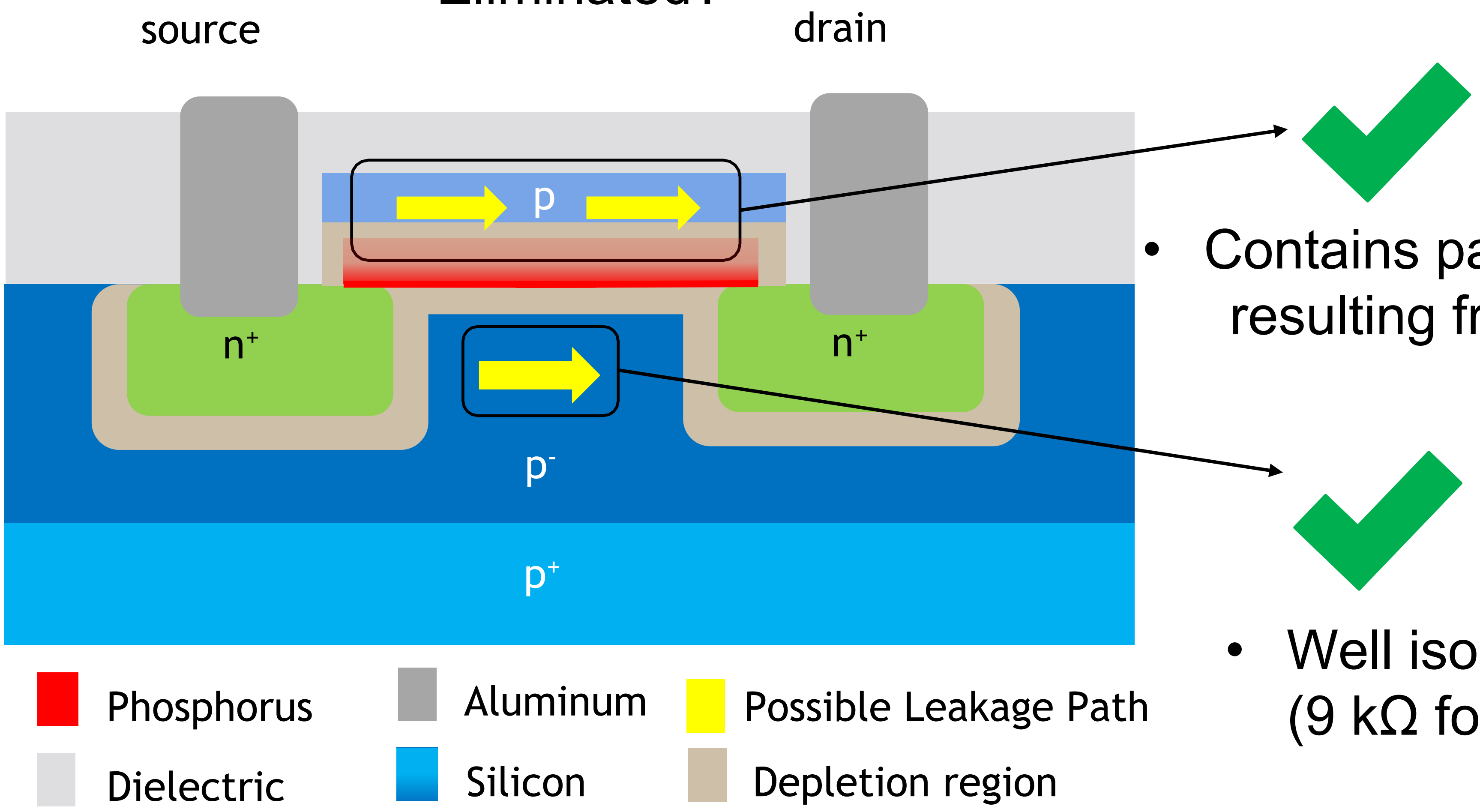
p-	B: ~$1x10^{16}$ atoms/cm^3
p++	B: ~$8x10^{18}$ atoms/cm^3



Joule Heating Temperature Control is Critical to Maintain Doping!

RT APAM: Addressing Leakage

Question: Have Leakage Pathways Been Eliminated?

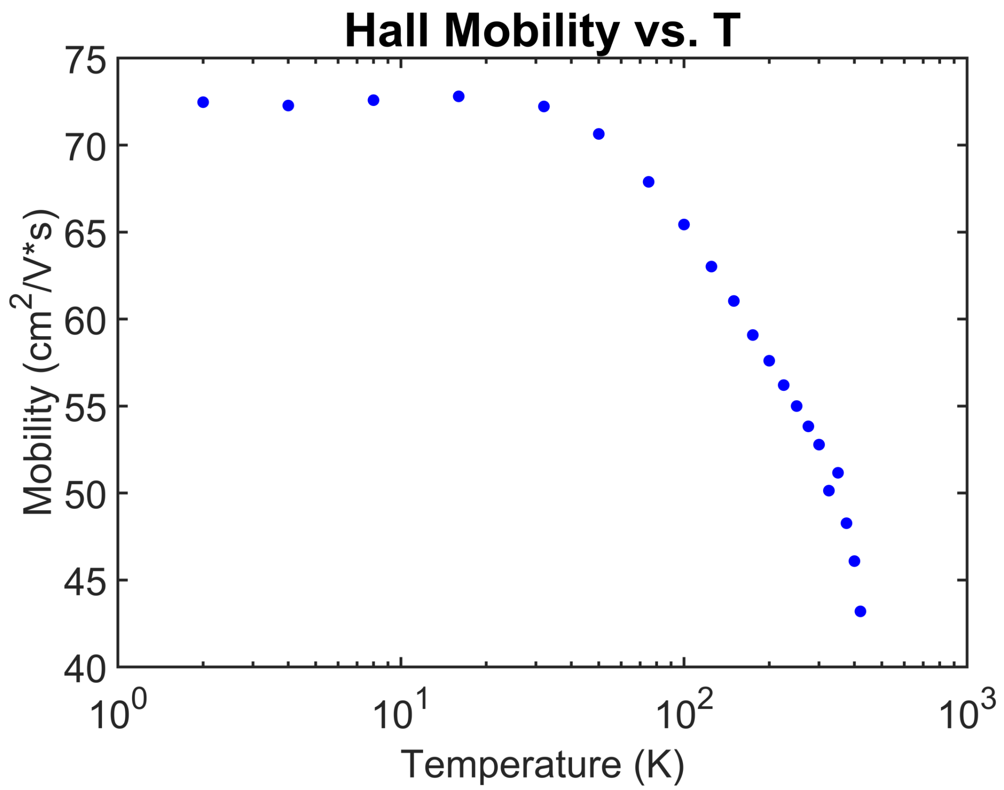


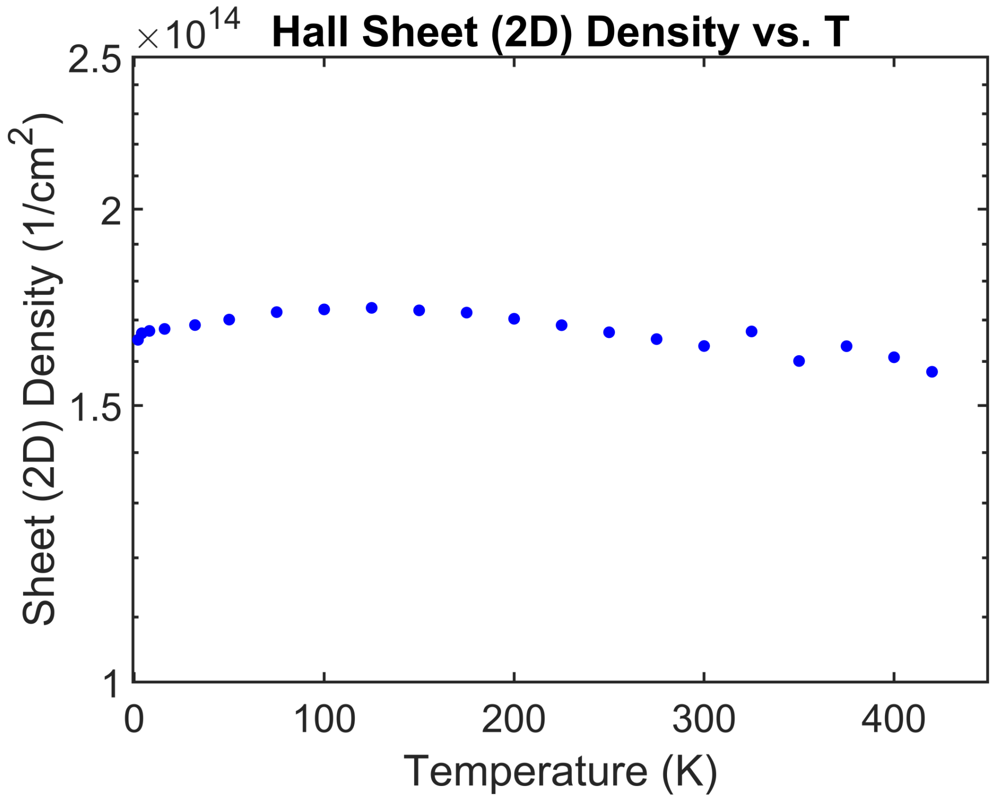
- Contains partially diffused P δ-layer, resulting from high temperature Si growth

- Well isolated relative to P δ-layer (9 kΩ for P δ-layer, 6 MΩ to p^+ handle)

Answer: Yes!

First-Ever Temperature Dependent APAM Hall Measurements



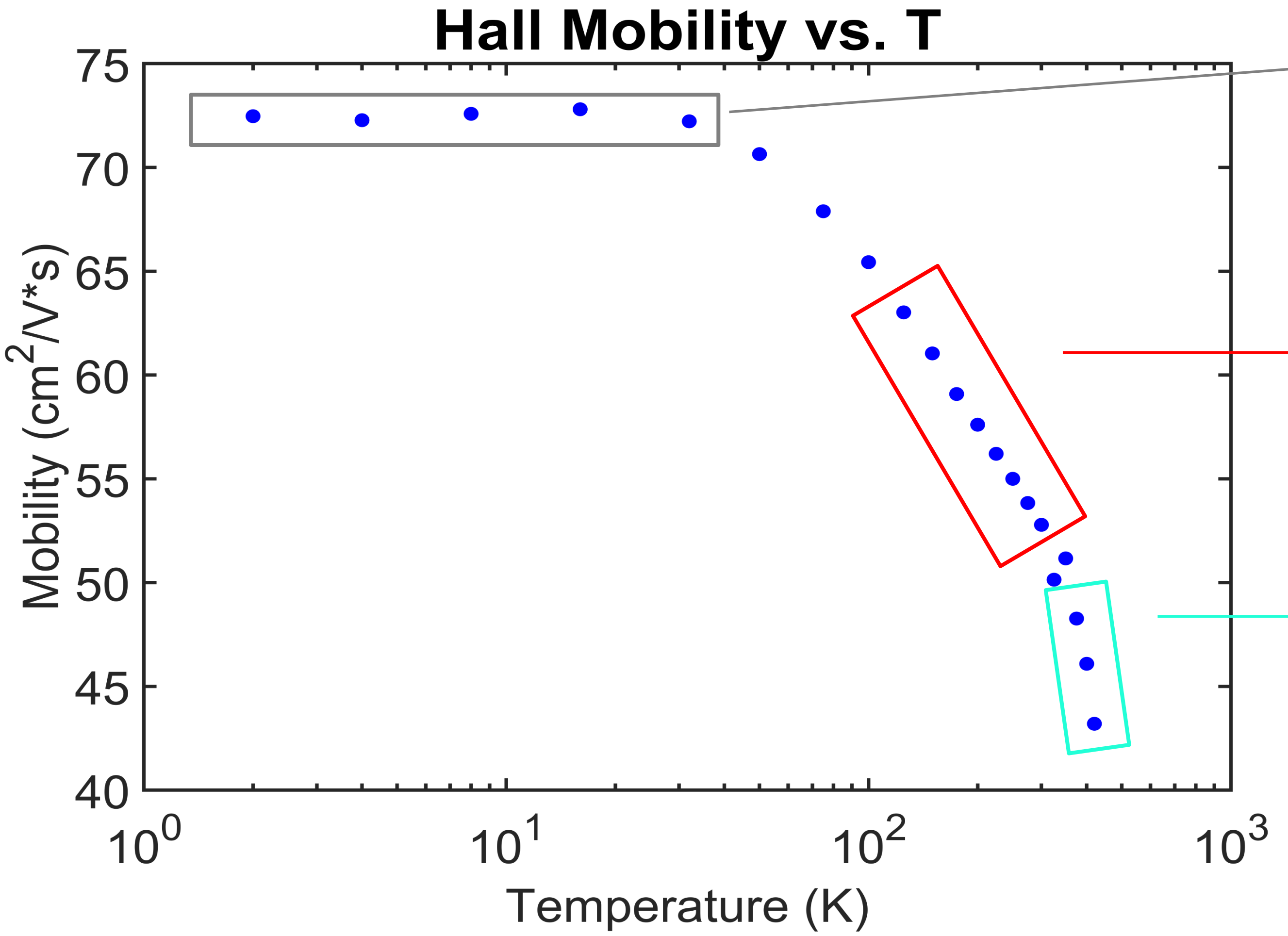


Mobility & 2D sheet density agree with previous IR-VASE ellipsometry measurements at RT

Katzenmeyer, A. M., J. Mat. Res, 35, 16 (2020)

Successful demonstration of new experimental platform for elevated temperature studies (2 – 425+ K)

Different Electron Mobility Regimes



10-50K: Expected to be dominated by el-impur interactions, T-independent

Ando, et. al. Rev. Mod. Phys, 54, 2, 437 (1982

75-300K: Expected to be dominated by el-phonon interactions, μ(T) ~ T
Matches previous 4-pt data

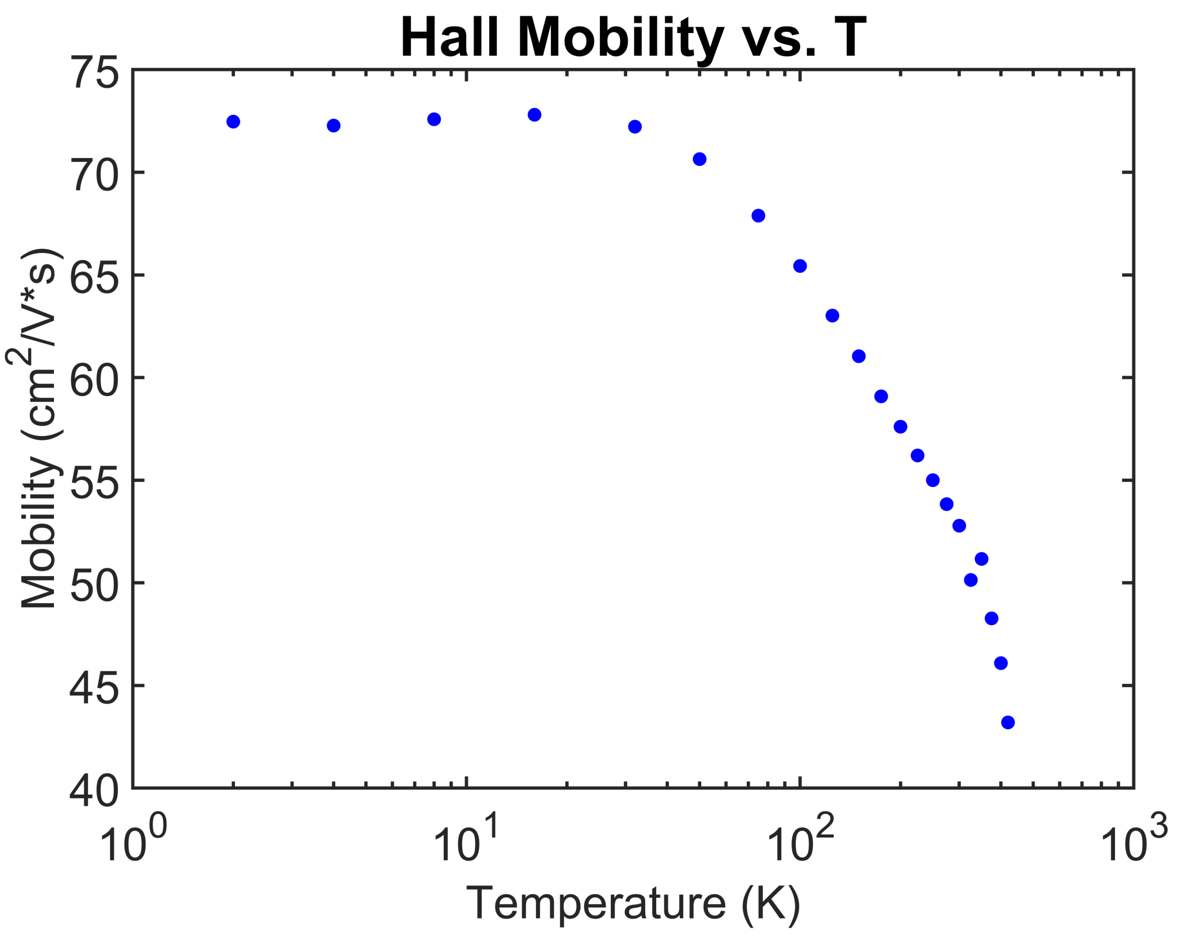
Mazzola, F., et. al. Appl. Phys. Lett., 104, 173108 (

350-425K: Should still be el-phonon but μ(T) suddenly has a much steeper slope.
Highly unexpected!

Takagi, S., *et. al. J. Appl. Phys*, **80**, 1567 (1996)

Unexpected μ(T) behavior in P δ-layer above 350K!

Prospectus



Use of MOS compatible counter-doping scheme enables RT operation of P δ-layer

Leakage pathways eliminated, with reduction of Si growth temperature eliminating P δ-layer diffusion

Unexpected temperature dependence of μ(T) of P δ-layer in Si above 350K

Establishment of new experimental platform for studying elevated temperature transport in nanoscale devices

Some of this work is supported by the Laboratory Directed Research and Development Program at Sandia National Laboratories, and was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National