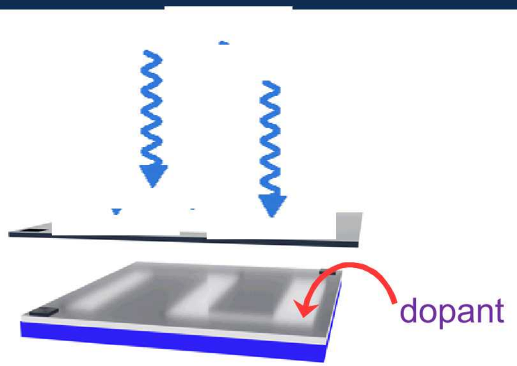
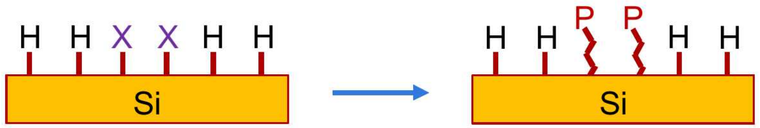
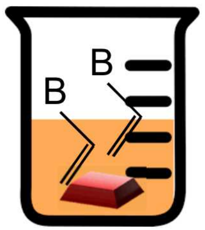
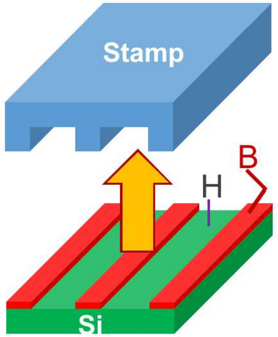
SAND2019-0241PE









FAIR DEAL GC Thrust 4: Application Platform

George T. Wang, Robert Butera, Aaron Katzenmeyer

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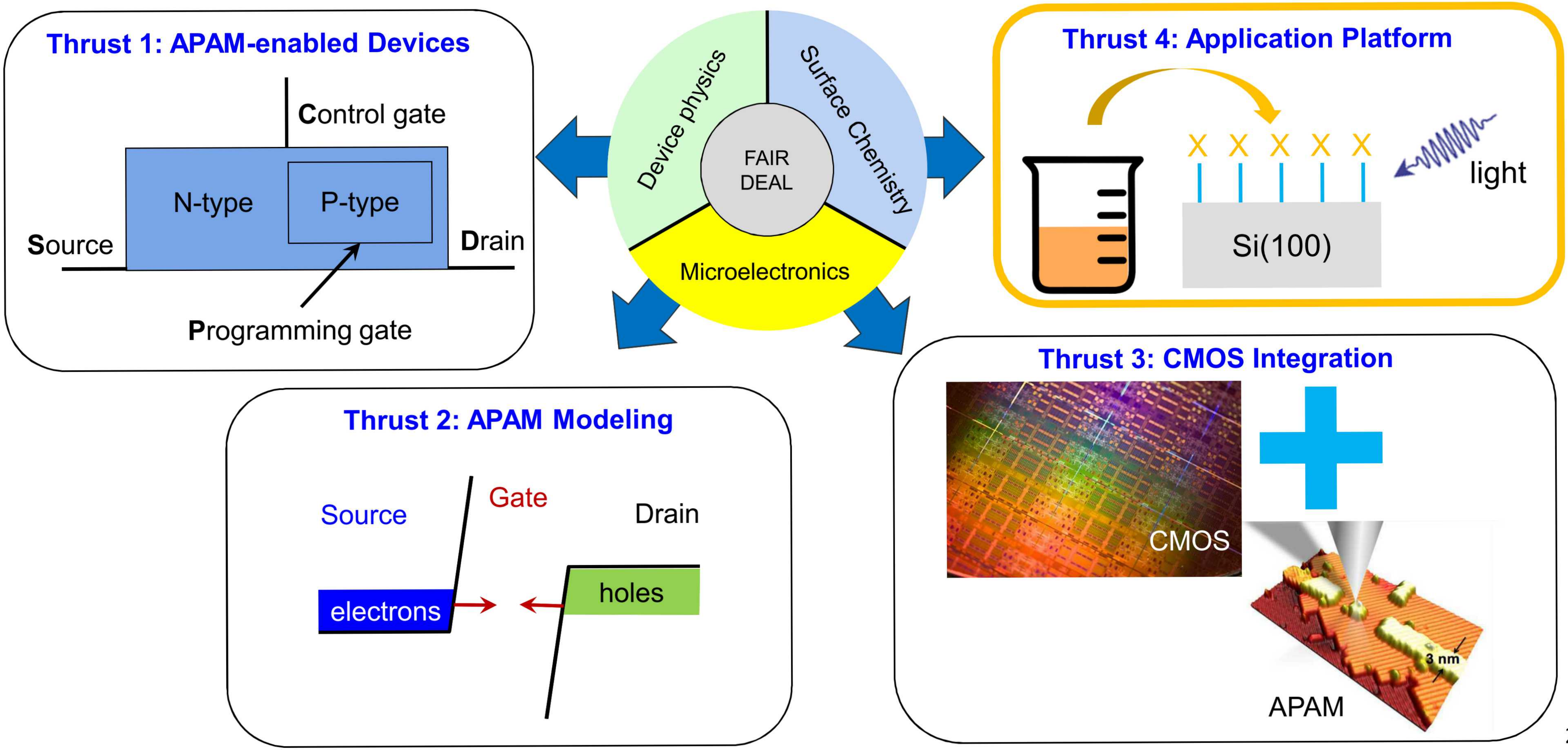
Digital electronics at the atomic limit (DEAL)



What if you could do atomic-scale processing?

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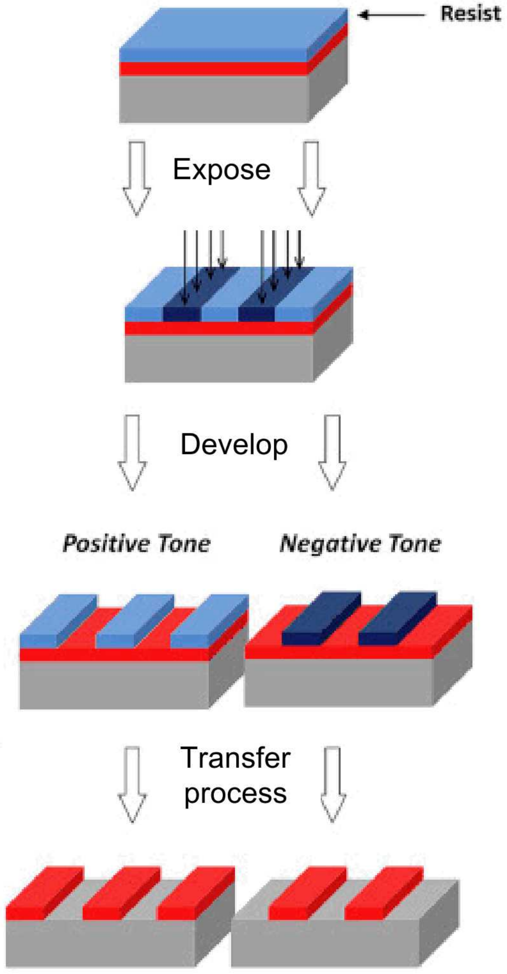
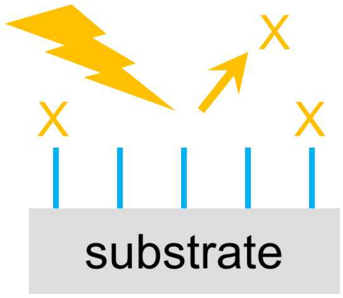
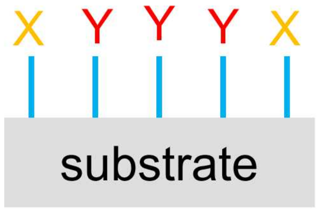


Traditional etch process

Unexplored, new phase space

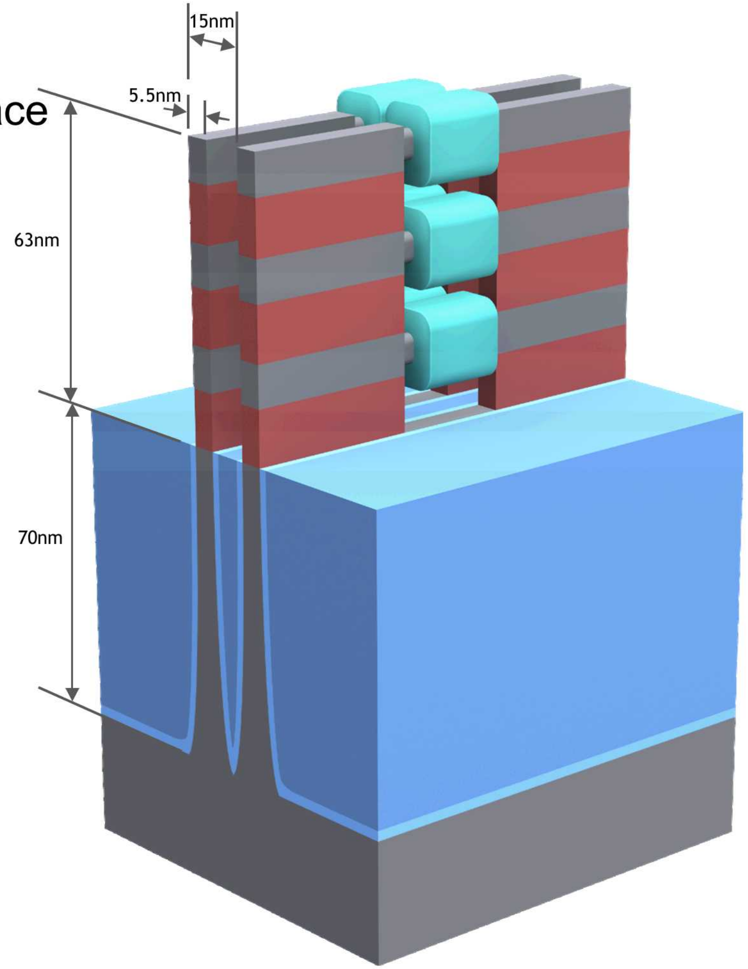


Expose & develop



Transfer process

Area selective chemistry



Produces material that defies expectation

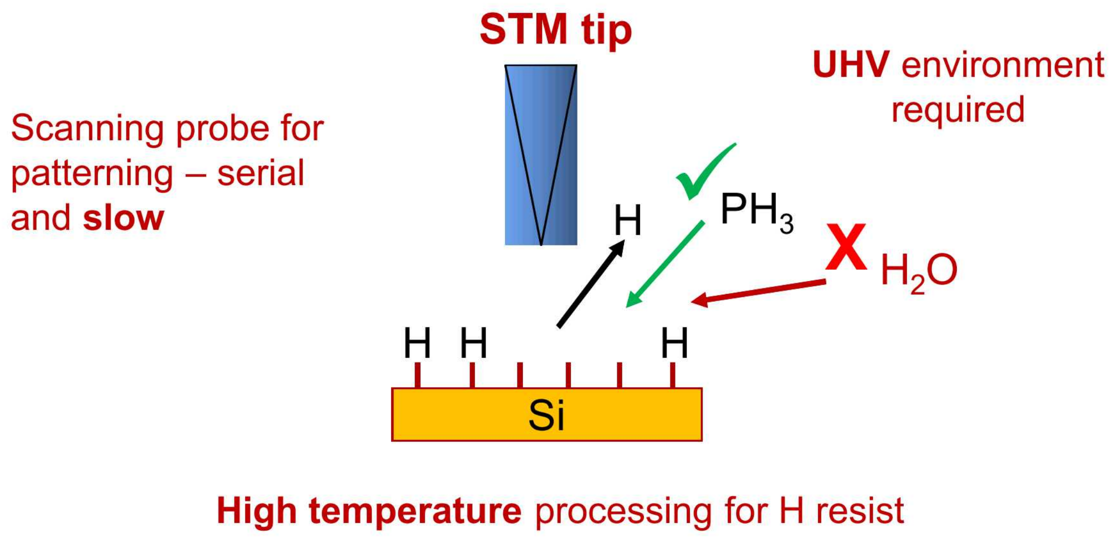
R. Arghavani estimates

Parameters	I_{ON} (mA/μm) @ $V_{GS}=V_{DS}=0.7V$
Si FinFET (H_{FIN}=37nm)	0.630
1 NW GAA	0.286
2 NW GAA	0.525
3 NW GAA	0.576
Si FinFET (H_{FIN}=54nm)	0.690

Compare to APAM: over 2 mA/ μm (cryogenic)

Problem: No current scalable path to manufacturability!

Current APAM : STM/UHV *Learning Platform*



Limitations

- **H resist** requires **UHV and high temp**
- STM-based **patterning** is **slow & requires UHV**
- Only one proven resist type (H) and dopant (PH_3) chemistry exists – **limits flexibility**

Opportunity

Scalable and patternable surface chemistries to enable new device manufacturing pathways and performance

Current APAM : STM/UHV *Learning Platform*

- Slow STM patterning
- Restricted to UHV
- Only one atomic resist (H)
- Only two dopants (PH_3 and tentatively B_2H_6)

APAM "*Application Platform*"

Rapid lithography

New atomic resists and dopants

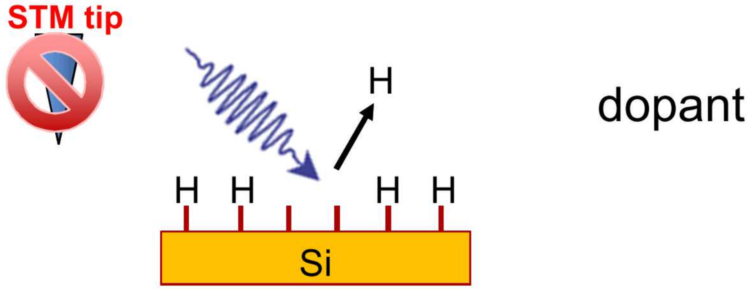
RT, Non-UHV, processes and chemistries

New principles & toolkits for rapid, scalable processing towards manufacturability!

Thrust 4: APAM Application Platform

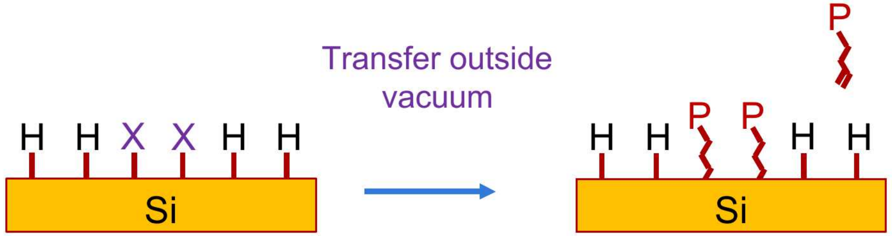
1. Photolithography

Explore optical induced pathways for patterning & doping atomic resists



2. Alternative Resists and Dopants

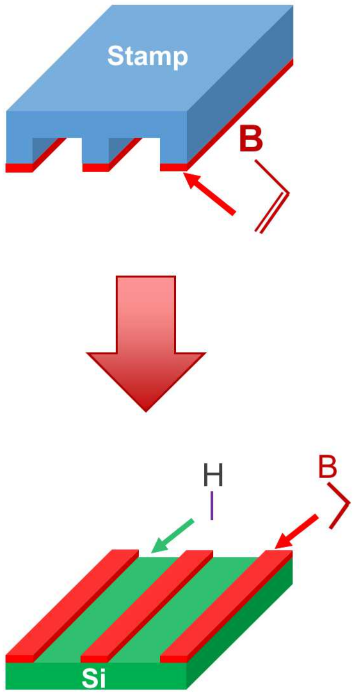
Explore alternative halogen resists for new dopant chemistries and complementary resists for pattern preservation outside UHV



X = Alternative Resist (Cl, Br, or I)

3. Patterned wet chemistries

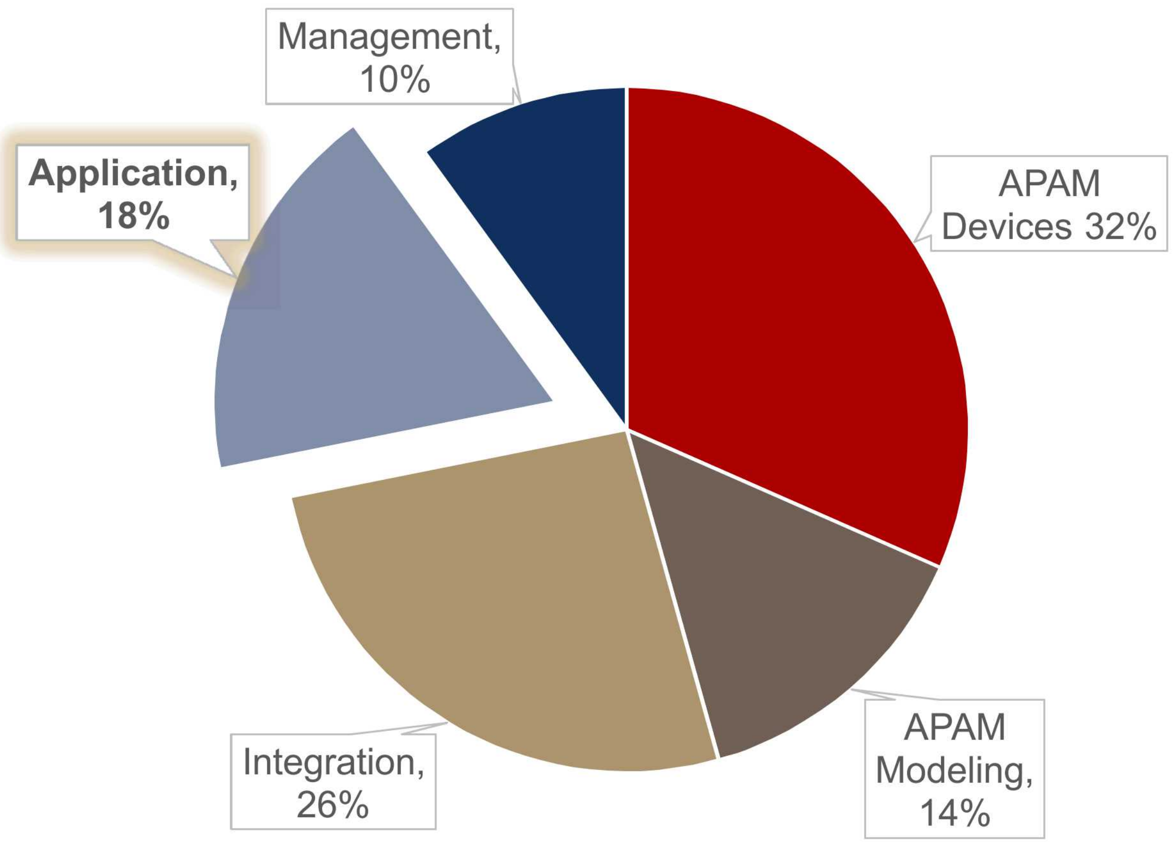
Discover robust and scalable wet surface chemistries for resists and selective area molecular doping



APAM Applications Platform Overview

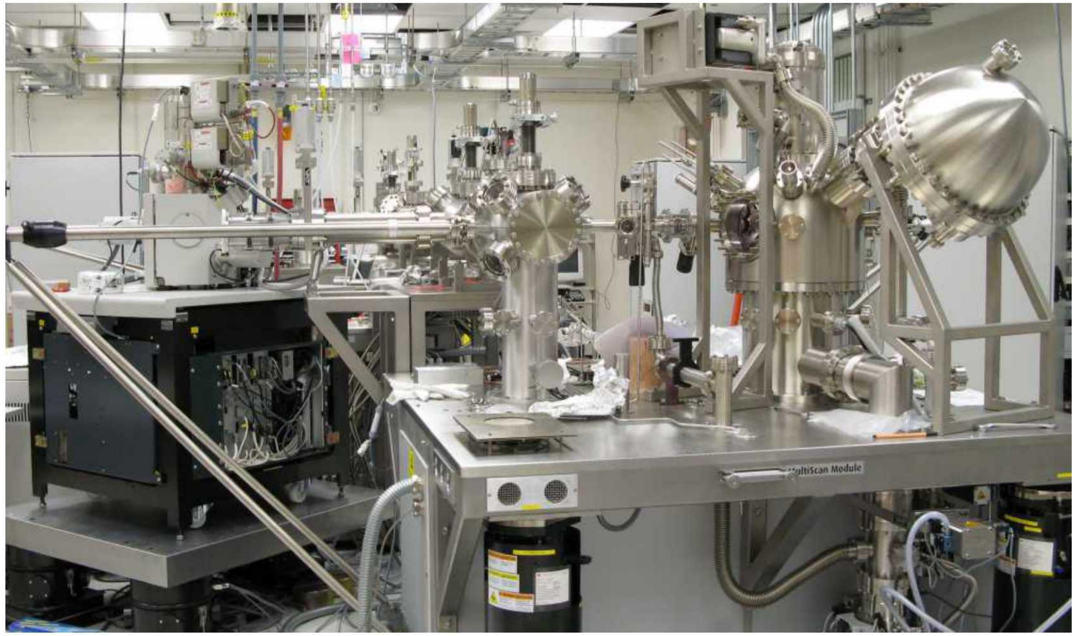
	Year 1	Year 2	Year 3
Photolithography	H-patterning by laser	Photolithography system build and test	**Patterned doping by photolithography**
Alternative Resists & Dopants	Alternative halogen resists	Complementary patterned H & halogen resists	**Selective dopant delivery to complementary resist**
Patterned Wet [Surface] Chemistries	Discover patterned wet chemistry for **acceptor**	Discover patterned wet chemistry for **donor**	**Patterned features with < 350 nm resolution**

Resources



Leverage MESA Advanced Nanotechnology Tool:

STM, XPS, Scanning AES, SEM, etc.



Organizational chart

Thrusts

Program Leadership
PI: Shashank Misra
PM: Robert Koudelka
Deputy PM: Rick Muller

#4 Application platform
Lead: George Wang
Photolithography: Aaron Katzenmeyer
Alternative resists: Bob Butera
Wet chemistry: George Wang

Support Team
Financial: Laurel Taylor
Logistics: Lori Mann
Web: Dorean Chaleunphonh
Administrative: Felicia Pena

Cross-cutting capabilities

Measurement: Lisa Tracy, Tzu-Ming Lu, David Scrymgeour, Ping Lu, Albert Grine

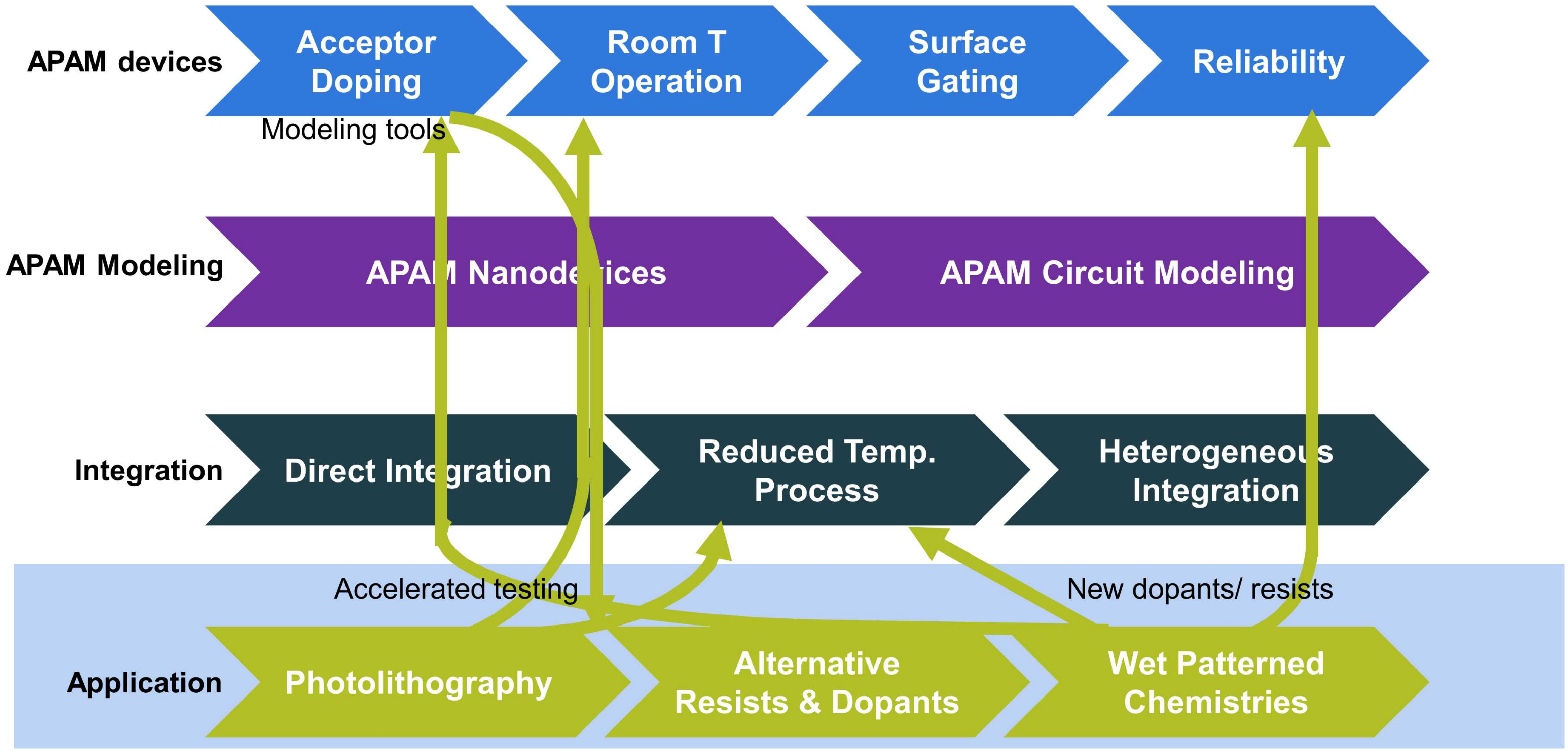
Microfabrication: Dan Ward, DeAnna Campbell, Mark Gunter, Steve Carr, Sean Smith

Modeling: Denis Mamaluy, Suzey Gao, Leon Maurer, Andrew Baczewski, Peter Schultz, Quinn Campbell

Surface science: Shashank Misra, Ezra Bussmann, George Wang, Aaron Katzenmeyer, Evan Anderson, Fabian Pena, Esther Frederick, Bob Butera, Dave Wheeler

Key task leaders in italics

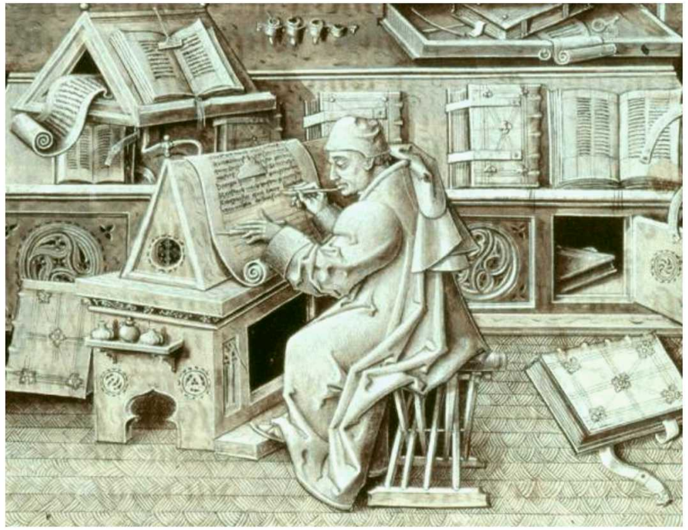
Cross-cutting benefits



Opportunity

Scalable and patternable surface chemistries to enable new device manufacturing pathways and performance

Current APAM : STM/UHV *Learning Platform*



Wikipedia, Scriptorium 2018

APAM "*Application Platform*"

Wikipedia, Printing Press 2018

New principles & toolkits for rapid, scalable processing towards manufacturability!

APAM Application Platform – Photolithography

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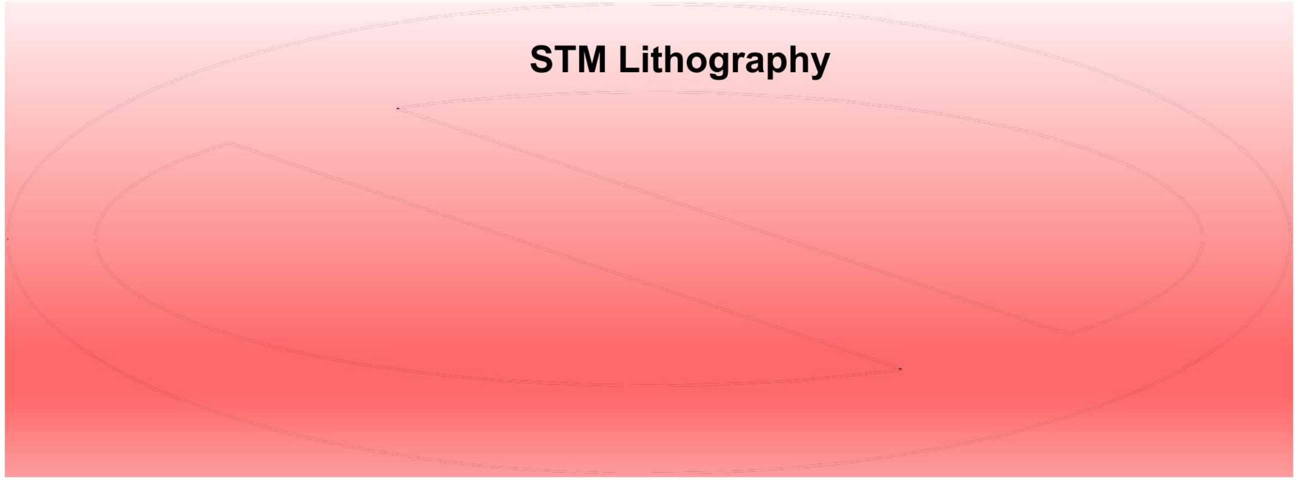
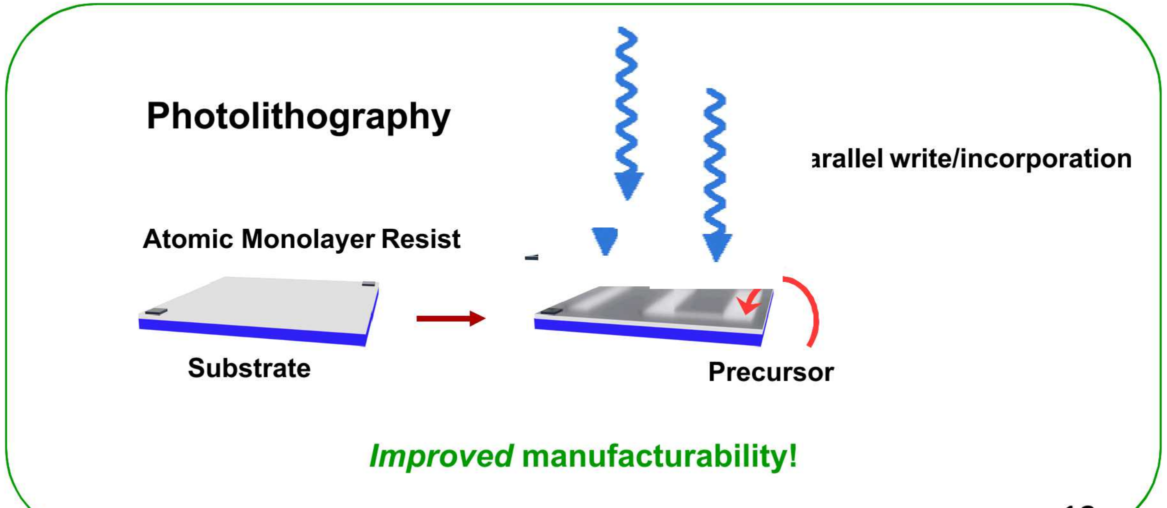
GOAL

Develop photolithographic APAM device workflows that:

- Are manufacturable - rapid, parallel, scalable
  (STM lithography: not manufacturable)
- Exploit unique advantages of atomic resists
  (Polymer resist: overexposure, instability…)

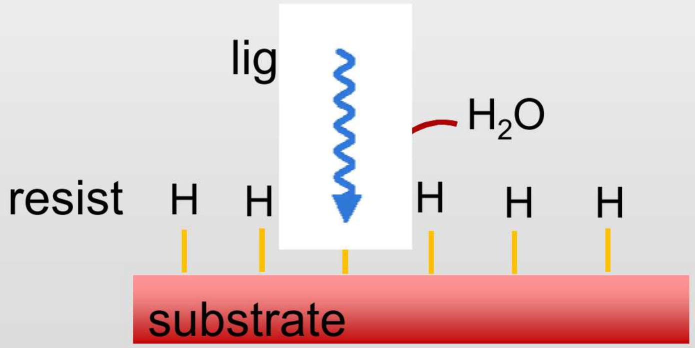




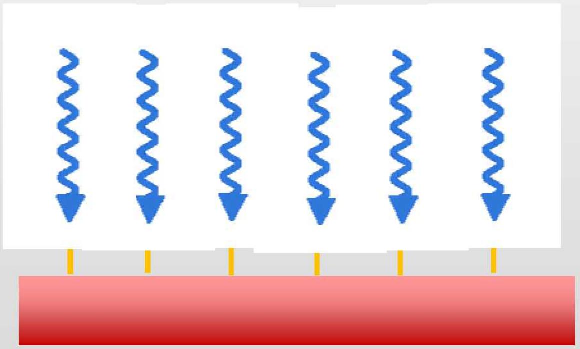
H Photolithography - SOTA

State of the art

- *Submicron features in H resist patterned in air using light*
- *H desorption using light in UHV (no patterning shown)*



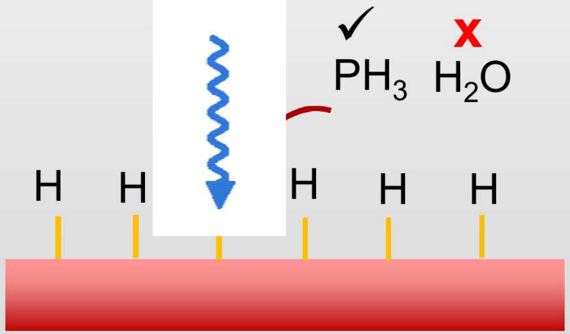
pattern, contamination



no contamination, no pattern

Needed

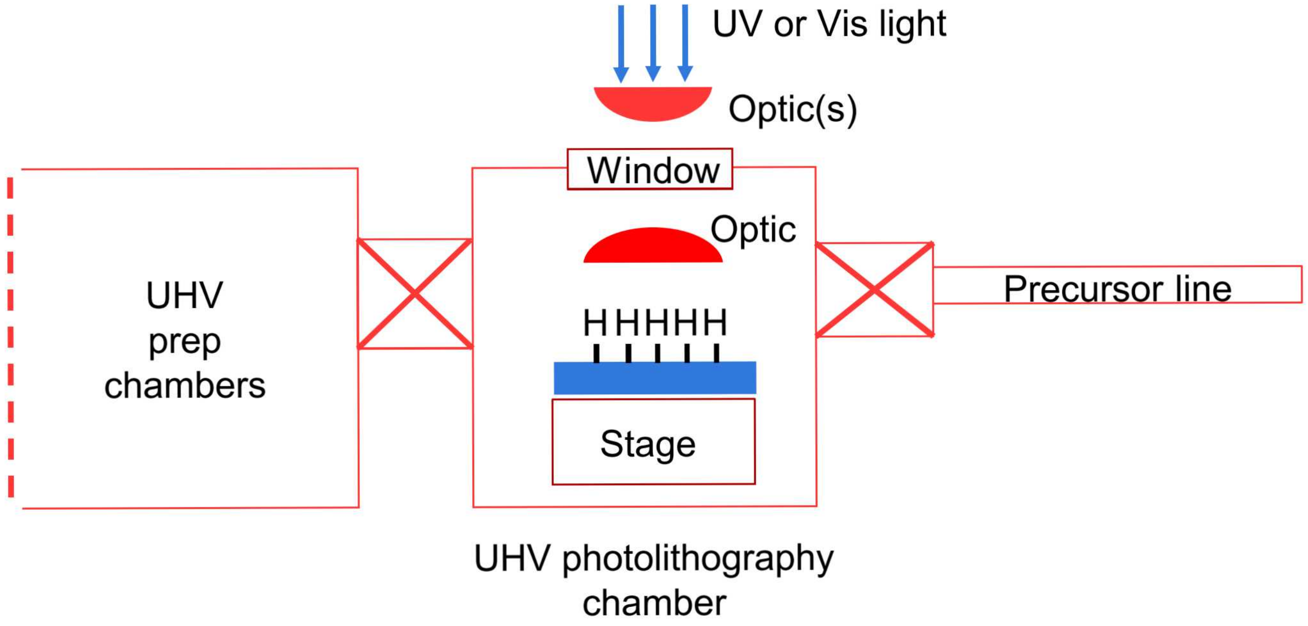
Pathway to:
- *Pattern small features (≤ micron)*
- *Add dopants*



pattern, no contamination

Photolithography - Strategy

Develop photolithography process for proven APAM system: H resist/PH_3 precursor



Engineer optics compatible with UHV processing, guided by theory/modeling

Photolithography - Risks

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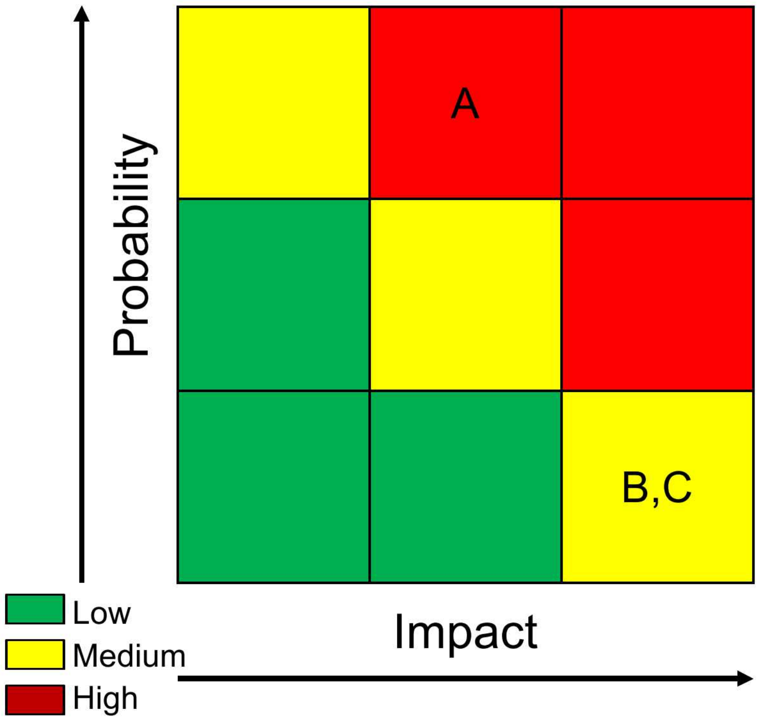
A. Physical mechanism of H photodesorption not understood
   Conflicting literature – wavelength, available optics?
B. Incomplete/insufficient desorption of H (limited doping)
   Quality of device as good as STM process?
C. Silicon surface damaged by process
   Catastrophic to fabrication process



Outlook and Impact

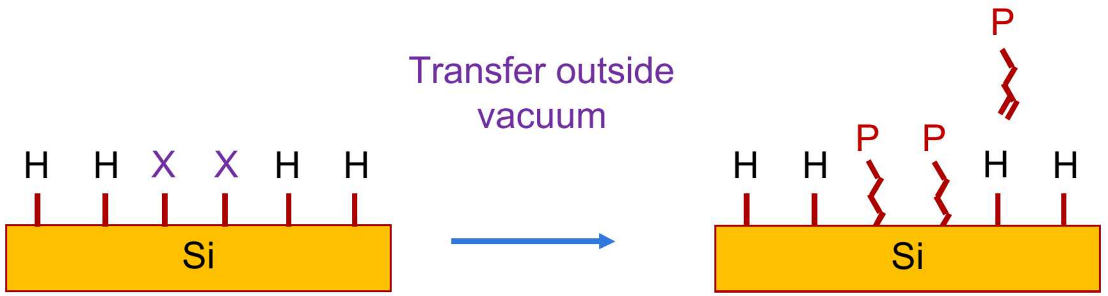
- Ability to manufacture P-doped Si devices
  Improves progress in all thrusts & tasks
- Theoretical & experimental framework for accelerated pathfinding of new:
  processes (dope-as-you-go), resists, dopants, environments (not UHV)
- Understanding potential of atomic resists for solving industrial problems

APAM Application Platform – Alternative Resist and Dopant Chemistries

GOAL: Alternative and complementary resist and dopant chemistries for APAM devices

- Current APAM process:
  - **Confined to UHV environments**
  - **Exclusively hydrogen-resist based chemistries (H resist + PH_3 doping)**

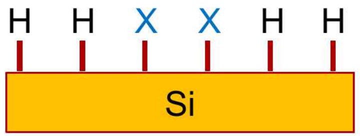
- FAIR DEAL:
  - **Develop complementary resist chemistries for pattern preservation and reaction outside UHV**
  - **Develop alternative atomic resists to expand possible dopant attachment chemistries**



Alternative and Complementary Resists: Current state of the art (SOA)

Current SOA*: Existing* halogen chemistries for silicon surfaces

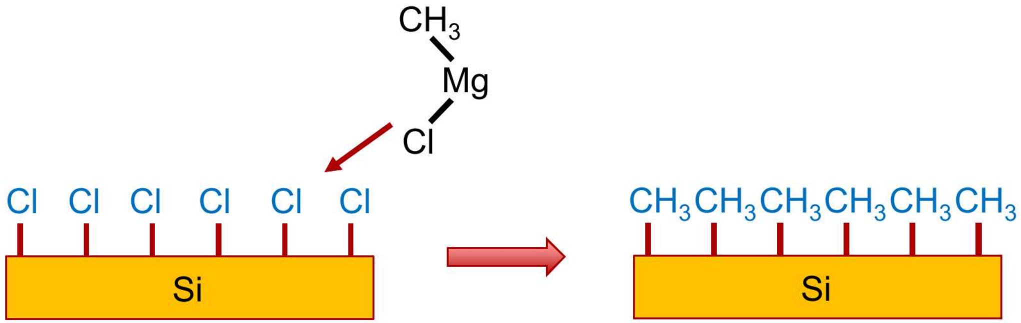
1. Halogen pattern fill on H-Si(100)



X = Cl and I

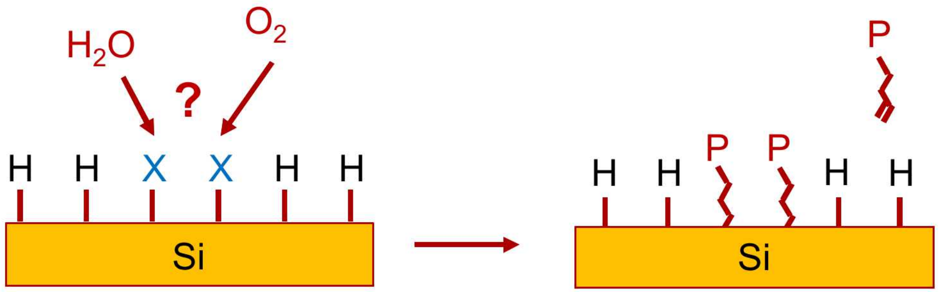
D.-S. Lin, *J. Chem. Phys.* **130**, 164706 (2009)

2. Alkylation of halogen-terminated Si(111)



N Alderman et al. *Appl. Phys. Lett.* **2013,** 103, 081603.

Needed: Test complementary pattern stability in ambient environment and selective area deposition of dopants



X = Cl, Br, or I

Risks

Goal: Alternative and complementary resist and dopant chemistries

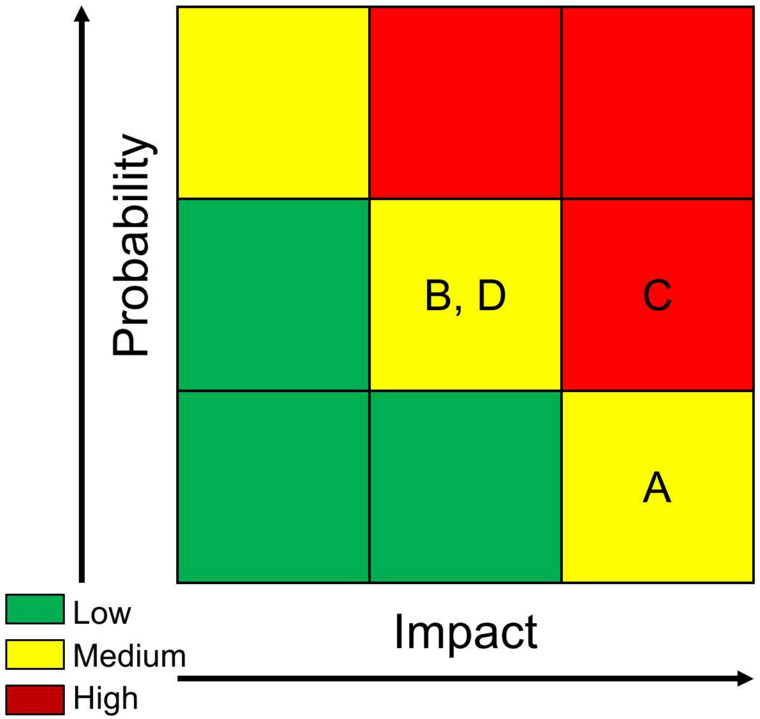
Challenges/Risks:

A. Resists not robust

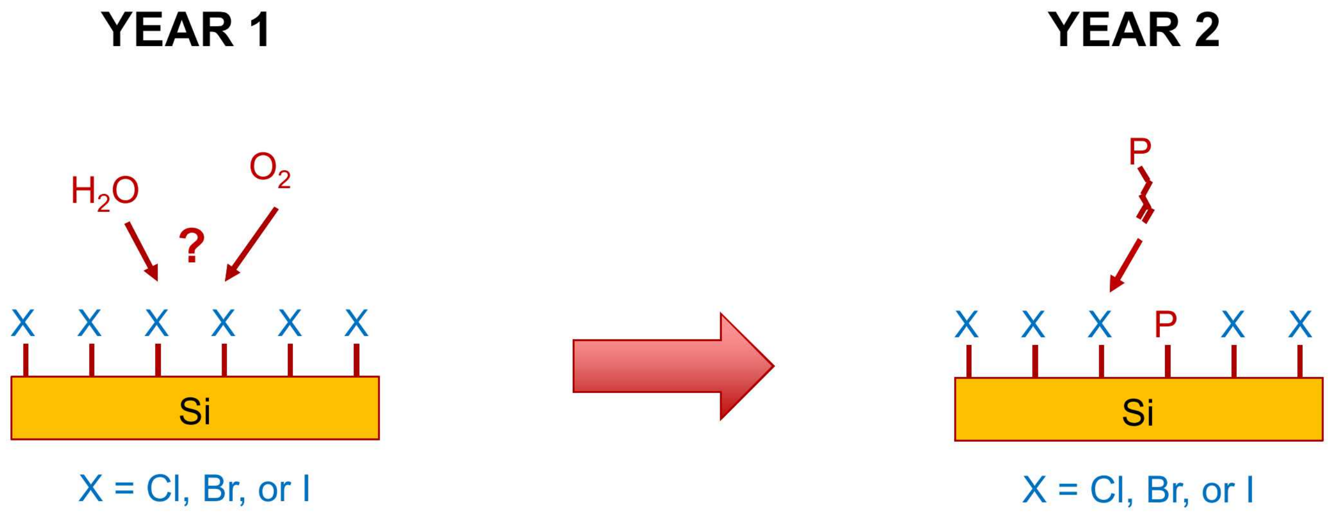
B. Incompatible process conditions with backend

C. No selective dopant chemistry pathway

D. Process detrimental to device performance



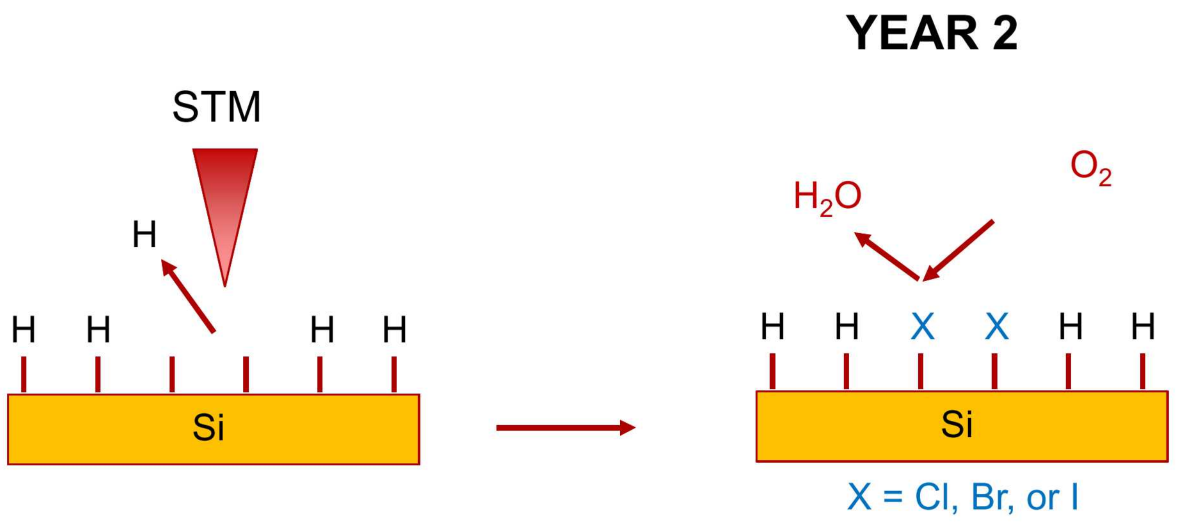
1. Develop alternative atomic resists to expand possible dopant attachment chemistries



Strategy: Alternative Resists

- Discover alternative, halogen-based atomic resists (in UHV)
- Test stability to inert and ambient environments
- Discover dopant attachment chemistries to alternative halogen resists

2. Create complementary resists for pattern preservation outside of UHV



<u>Strategy</u>: <u>Pattern Preservation via Complementary Resists</u>

- Pattern and passivate dangling bonds with alternative halogen resist to create "complementary resist"
- Test stability to inert and ambient environments

3. Selective dopant attachment to patterned complementary resist

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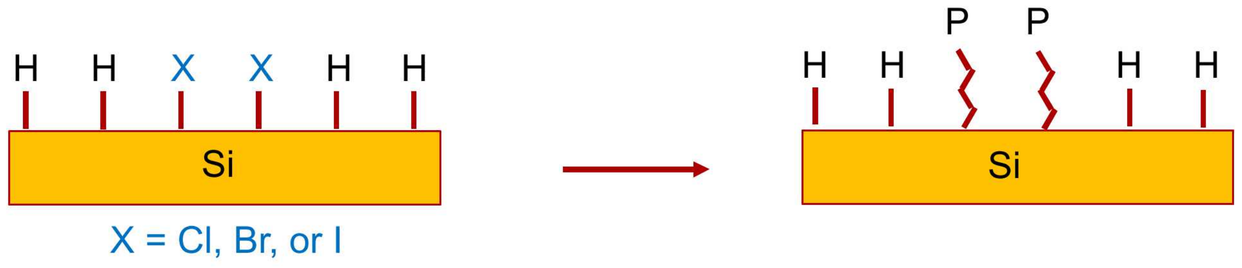
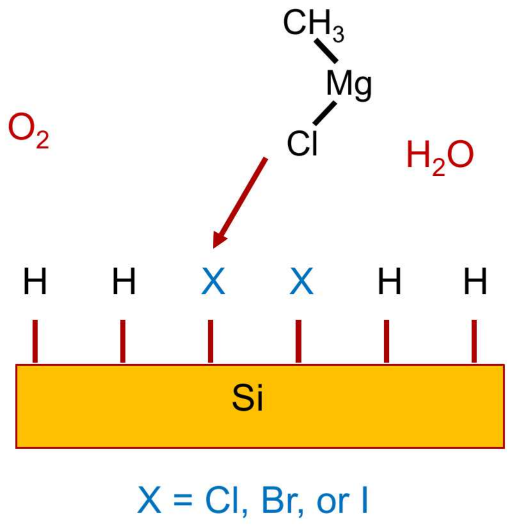
YEAR 3



Strategy: Pattern Preservation via Complementary Resists

- **Requirement**: Maintain difference in chemical reactivity of patterned resist (X) compared to surrounding resist (H) for subsequent dopant attachment chemistry
- Vacuum (gas-phase) or wet solution (mitigation path) chemistries
- Investigate **selective dopant attachment chemistry** to patterned areas (vacuum or wet solution)

Impact



Alternative resists opens door to expanded range of dopant attachment chemistries

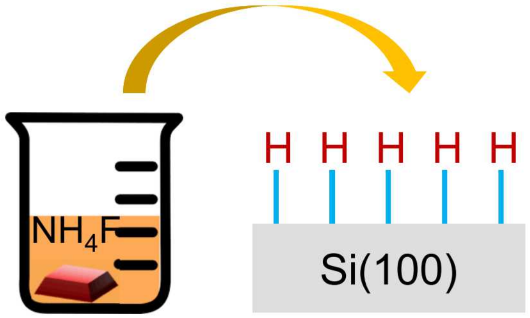
- Modeling to evaluate new attachment chemistries
- New path to acceptor dopants
- Enables complementary resists for pattern preservation for processing outside UHV
- Relevant for gas-phase and wet chemistries

APAM Application Platform – Patternable Wet Surface Chemistries

GOAL: Scalable, patterned wet chemical pathways for APAM devices

Current SOA: *Existing* Si(100) wet chemistry elements for APAM

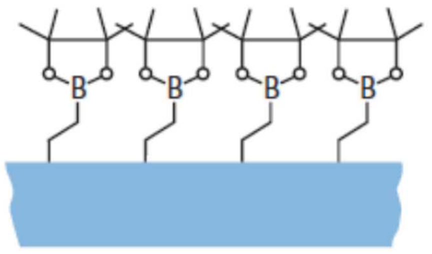
H resist on Si(100) by wet chemistry



Hines, J Phys. Chem C, 2012

H resist

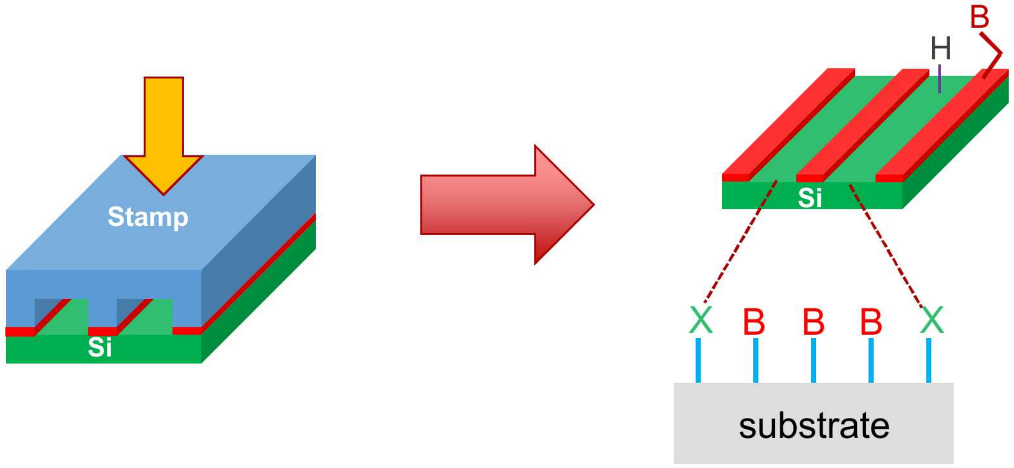
Molecular doping of Si(100)



Javey, Nat. Mat, 2007

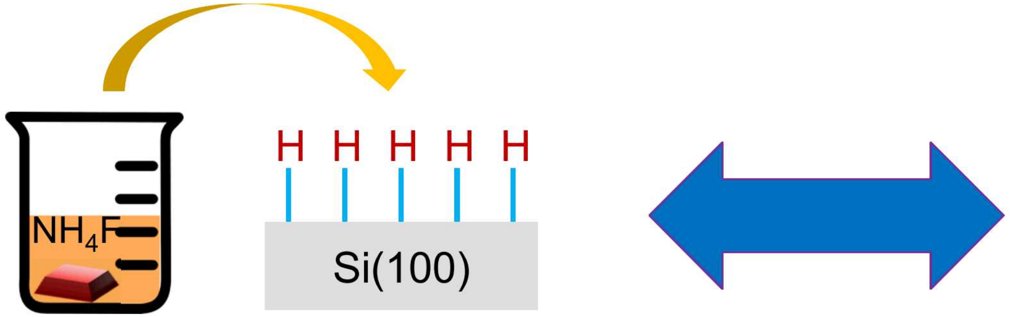
doping

Needed: Integrate new elements to enable **patterned**, selective area surface doping

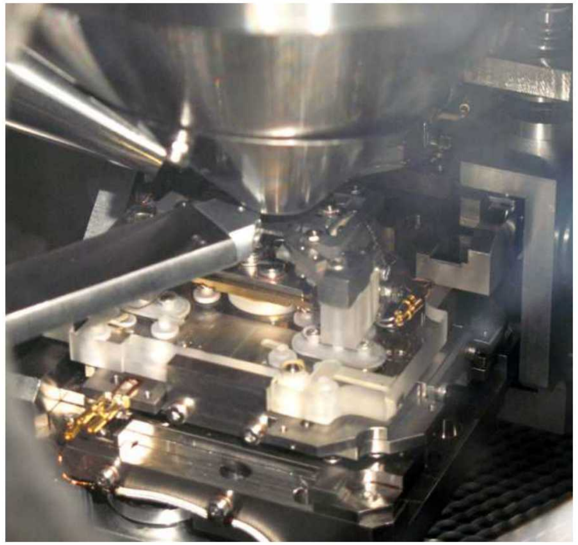


- **Advantages: highly inexpensive, scalable, accessible**
- **Also draws on large body of potential wet surface chemistries!**
- **Tradeoff: worse lateral resolution**

1. Develop robust, scalable wet chemical process for H resist on Si(100)



Characterize surface (morphology, coverage, impurities, defects) with surface analysis techniques: STM, XPS, FTIR, EDS, AES

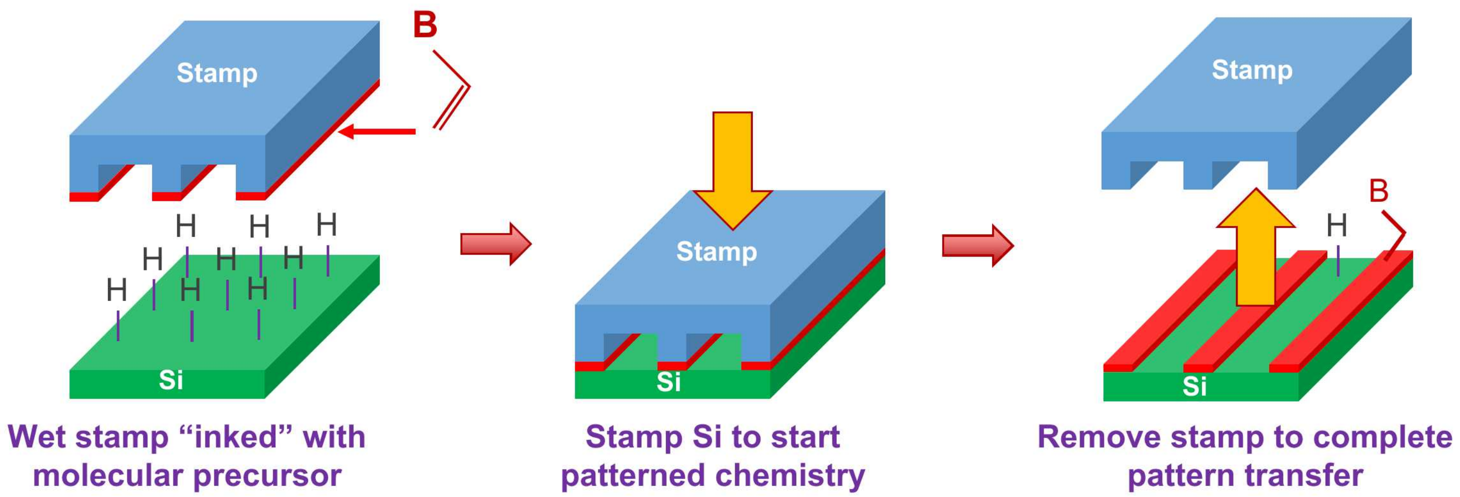


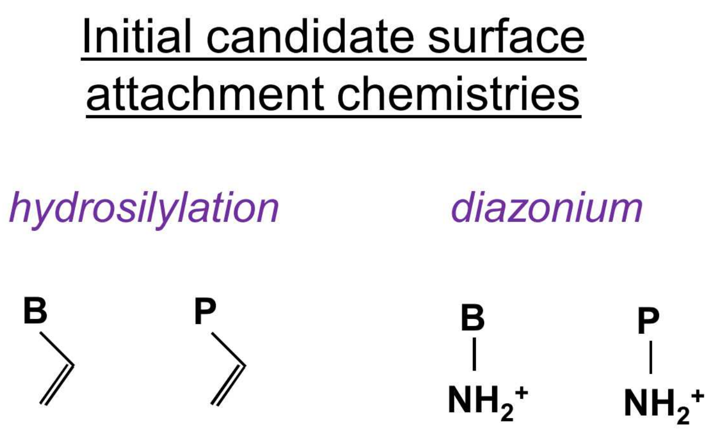
“Same-spot” multi-characterization: MESA ANT

IMPACT: Enable a rapid and inexpensive method for near *room-temperature* resist preparation

NEXT: How to incorporate dopant?

2. Discover wet, *soft-lithographic* processes for selective area molecular doping





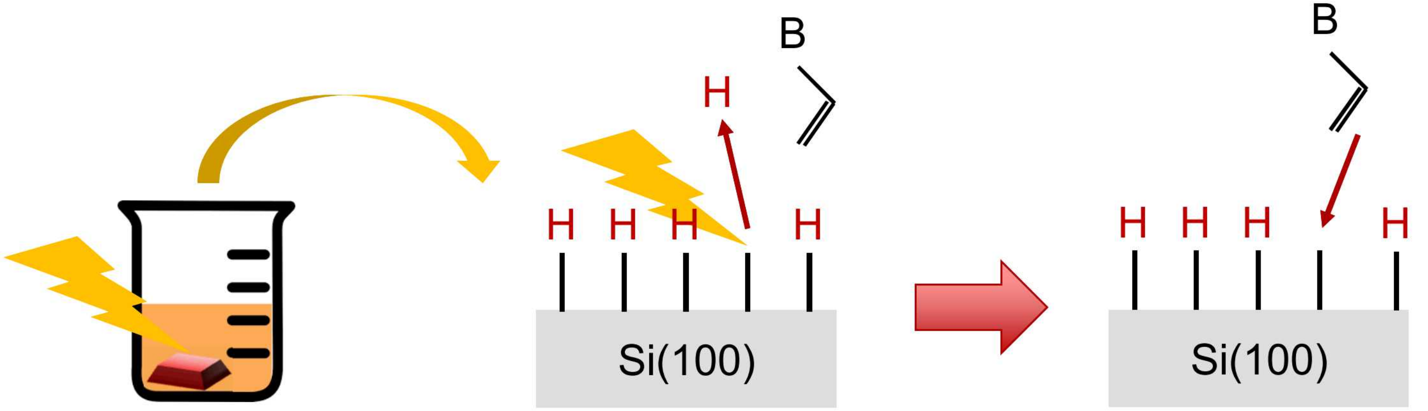
STRATEGY: Discover scalable, cheap, large area, soft-lithographic routes for dopant patterning

IMPACT: Enable a new, scalable, inexpensive process for patterned surface doping

- Potential **path down to < 10 nm resolutions!**
- Mitigation path for UHV **acceptor** doping and complementary doping/devices

2a. Mitigation: Discover wet *photolithographic* processes for selective area molecular doping

What is soft-lithography approach doesn't work?



Photochemical "dope-as-you-go" (wet chemical version)

<u>IMPACT</u>: Enable a new, scalable, inexpensive process for patterned surface doping

- Possible compatibility with current photolithographic fab processes

Risks

Goal: Wet chemical processes for H resist preparation and selective area attachment chemistry of dopants

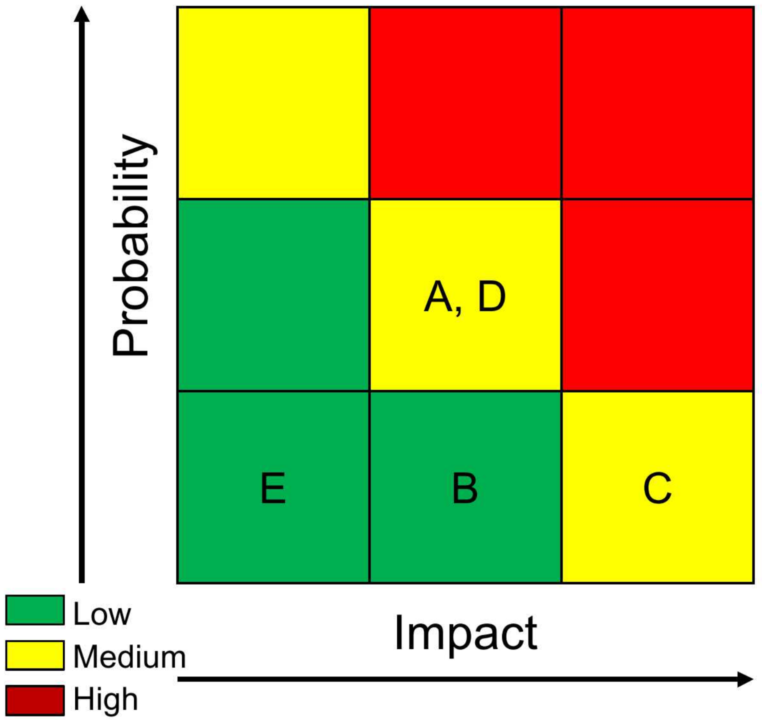
Challenges/Risks:

Wet H resist:

A. Poor quality surface

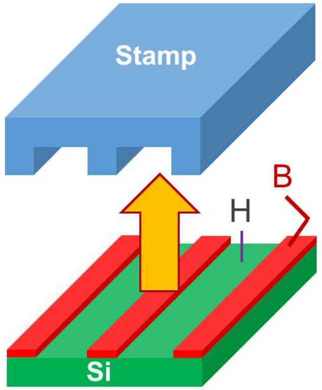
Selective area dopant wet chemistry

B. Compatibility of polymer stamp
C. Low reaction efficiency: low yield of dopants to surface.
D. Light scattering effects
E. Incorporation of undesired functional groups present in precursors (e.g. O)



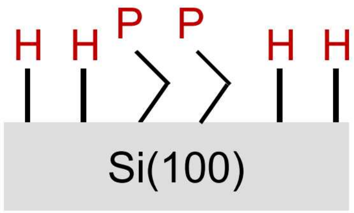
Outlook and Impact

Year 1



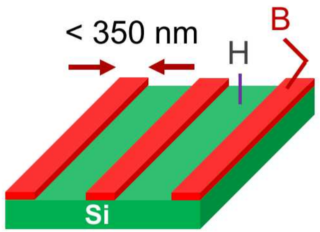
Proof-of-concept patterned **acceptor (B)** wet chemistry by soft-lithography (mitigation: wet photolithography route)

Year 2



Extend to patterned **donor (P)** wet chemistry

Year 3



Push patterned resolution down to **submicron scale** (< 350 nm) and beyond at chip scale

Opens up APAM to much wider community and knowledge/process base!