Tool- and pattern-dependent spatial variations in silicon deep reactive ion etching

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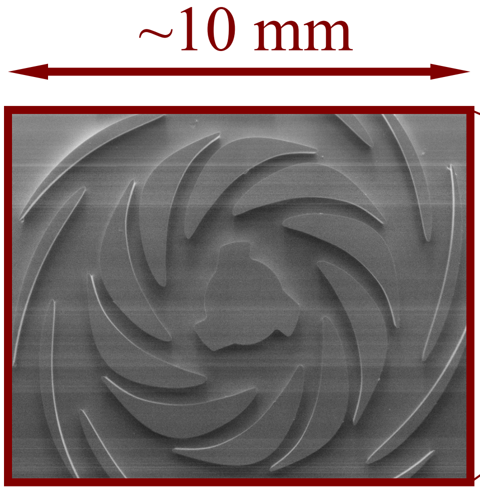
Coping with spatial variation in DRIE

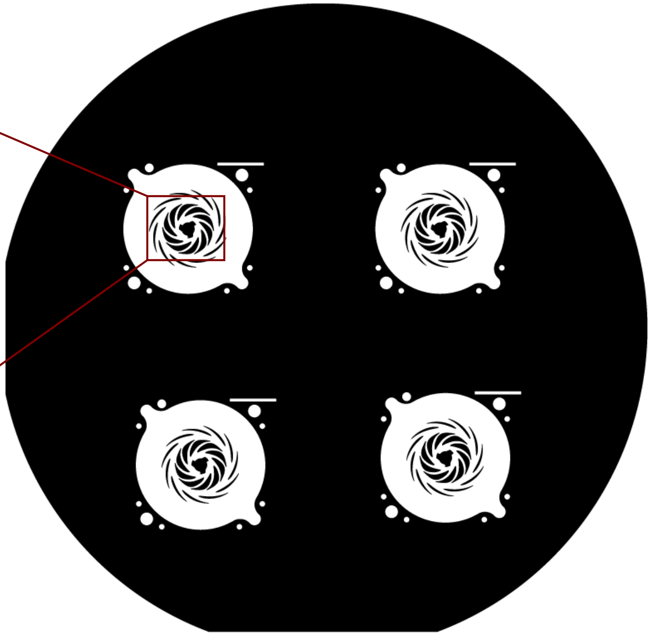
- Why non-uniformity is a problem
- Controlling uniformity with the mask design
- Characterizing tools' performance
- Wafer-to-wafer effects
- Improving the mask design process

Non-uniformity problems in MEMS

Aim: remove imbalance in MIT Microengine rotor



SEM picture
of turbine blades

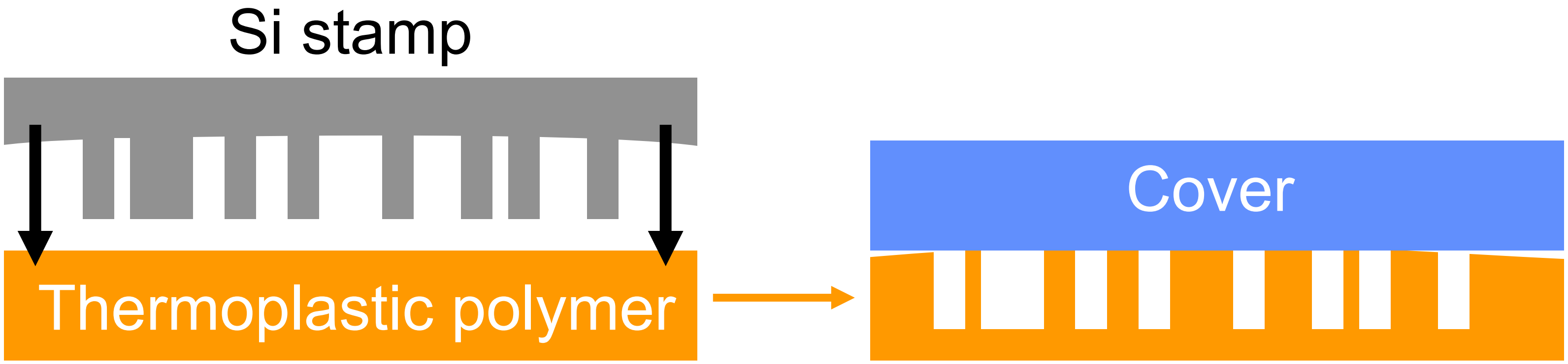


Mask layout

e.g.: A.H. Epstein *et al.*, Proc. Transducers '97

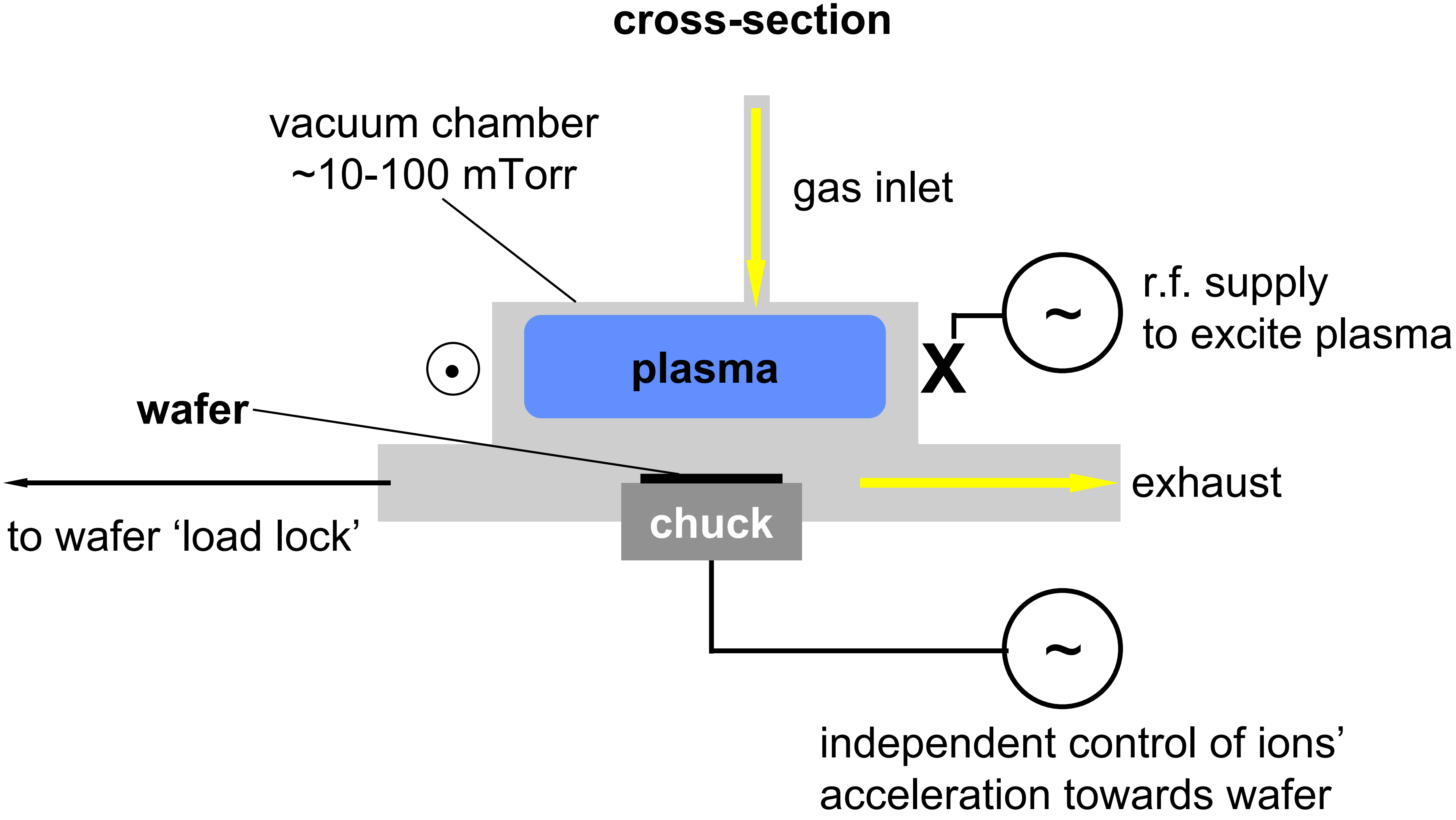
Non-uniformity problems in MEMS

also:
embossing stamp fabrication for microfluidics manufacture

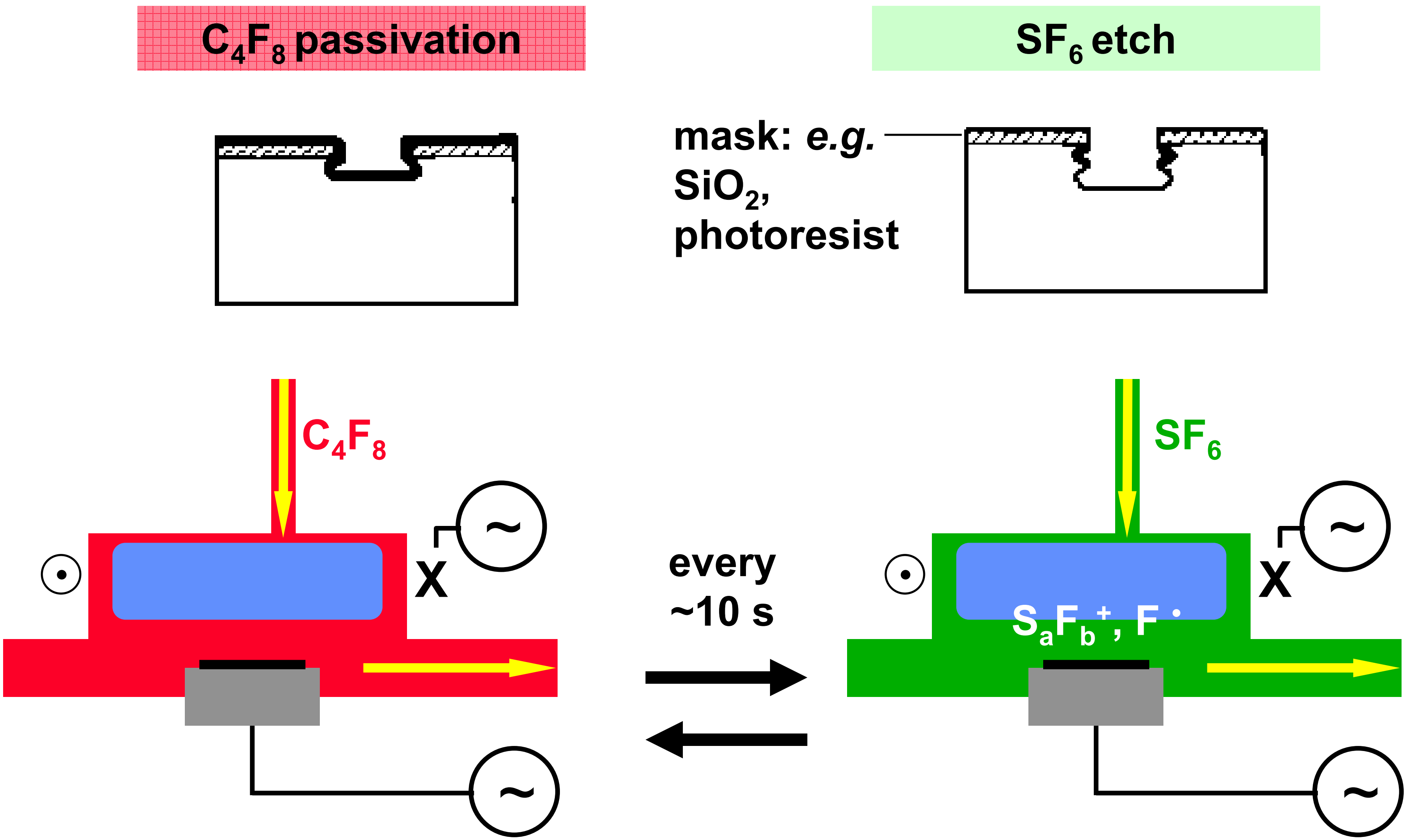


perhaps too: avoiding footing during SOI etch-through

Inductively-coupled plasma in DRIE chamber



Time-multiplexed ‘Bosch’ processing



C_4F_8 passivation

SF_6 etch

mask: *e.g.* SiO_2, photoresist

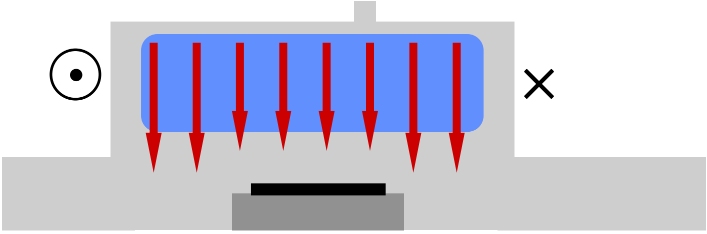
every ~10 s

Journal of The Electrochemical Society, 146 (1) 339-349 (1999);
Robert Bosch GmbH, Pat. 4,855,017 and 4,784,720 (USA) and 4241045C1 (Germany) (1994)

Non-uniformity at three length scales

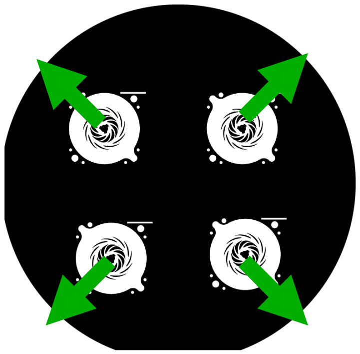
spatial variation

- **feature-scale**
  - aspect ratio-dependent etching (ARDE)
- **inter- and intra-device**
  - competition for reactants; diffusion
- **wafer/chamber-scale**
  - ion and radical flux distribution
  - wafer-level 'loading'



Strategies for improving uniformity

- **Force etching to be reaction-limited**
  - Lower chamber pressure
  - Wafer cooling
- **Conservative mask design** →



- **Improved tool design**
- ***Relate mask design directly to non-uniformity***
  - Design mask according to desired uniformity
  - Perturb etch rates constructively

Non-uniformity at three length scales

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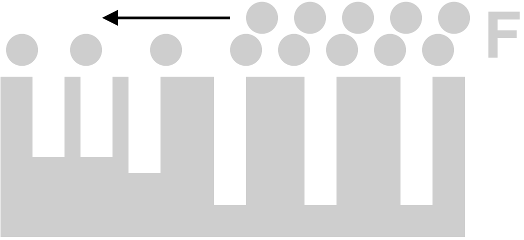
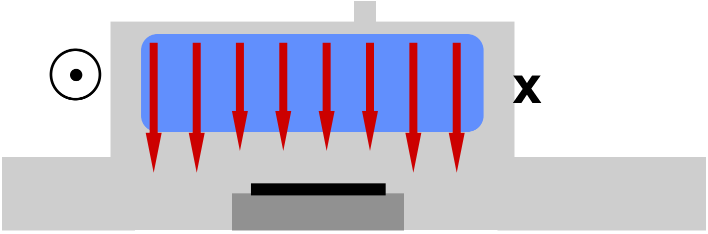
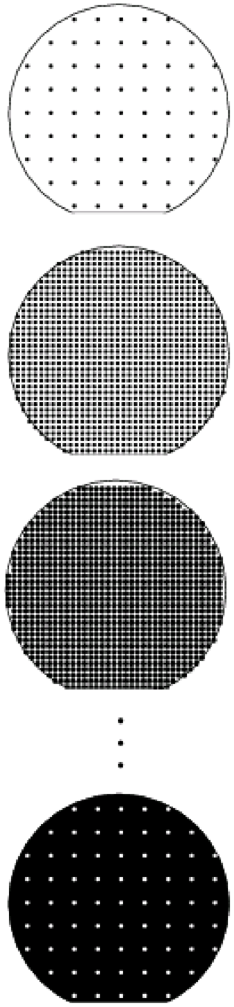
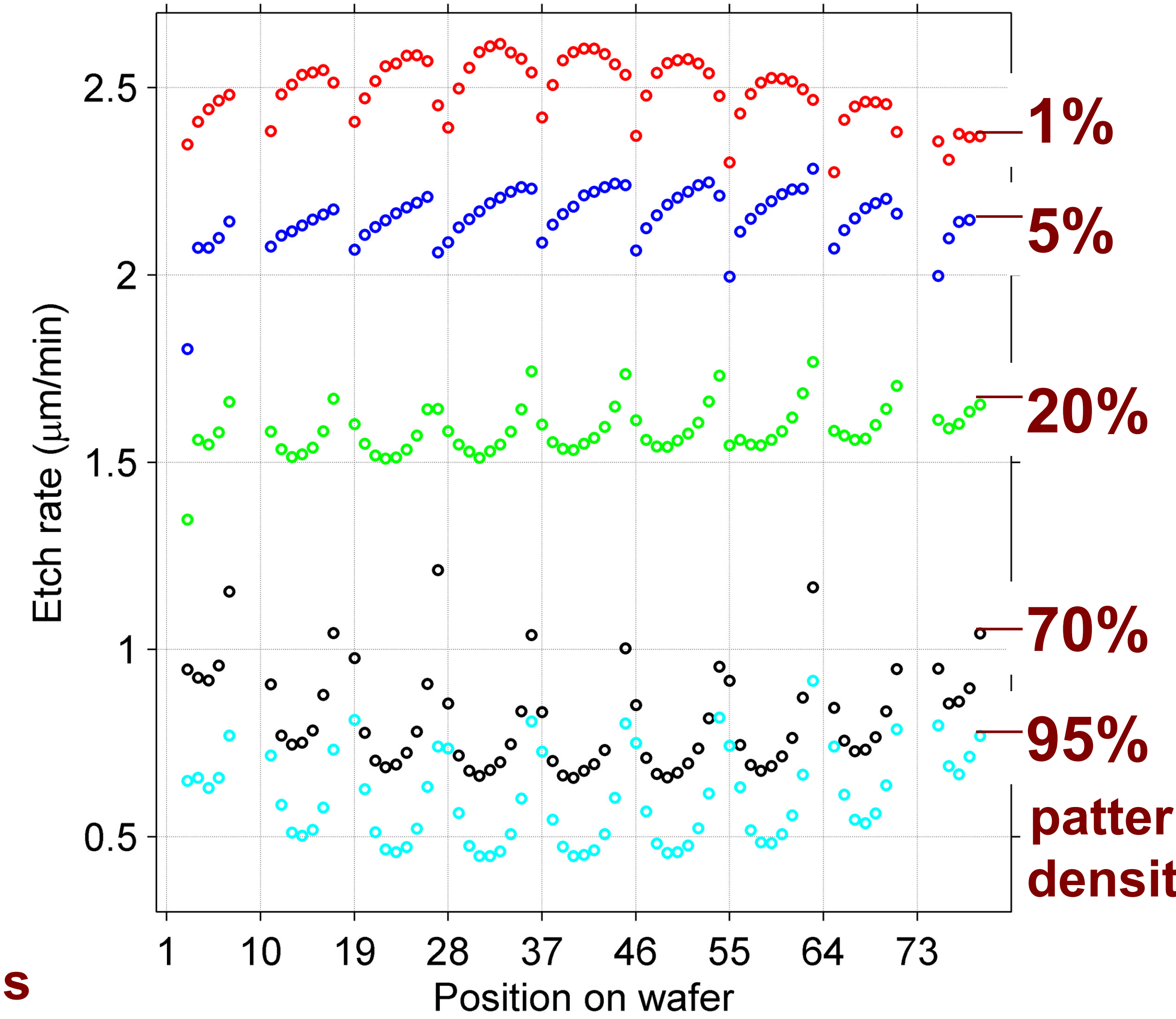


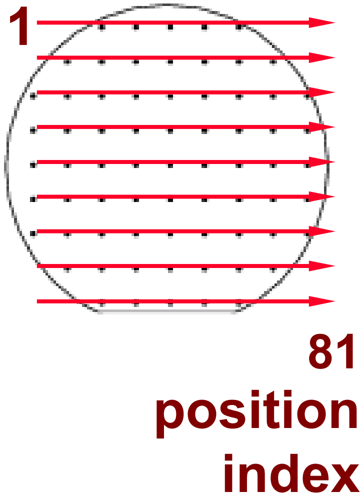


Previously observed chamber-scale variation



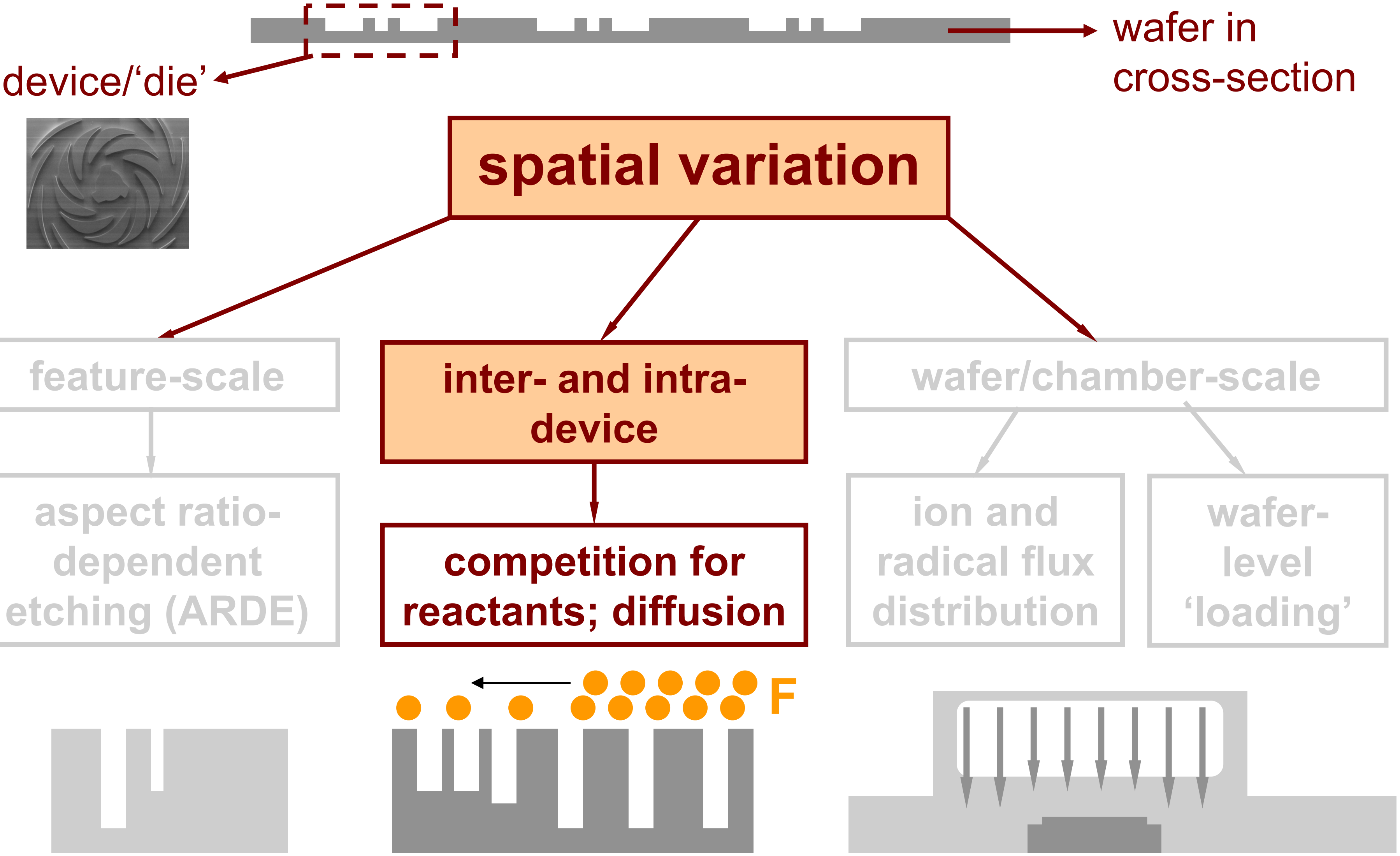
test patterns





H.K. Taylor *et al.*, submitted for publication

Non-uniformity at three length scales



device/‘die’

wafer in cross-section

spatial variation

feature-scale

aspect ratio-dependent etching (ARDE)

inter- and intra-device

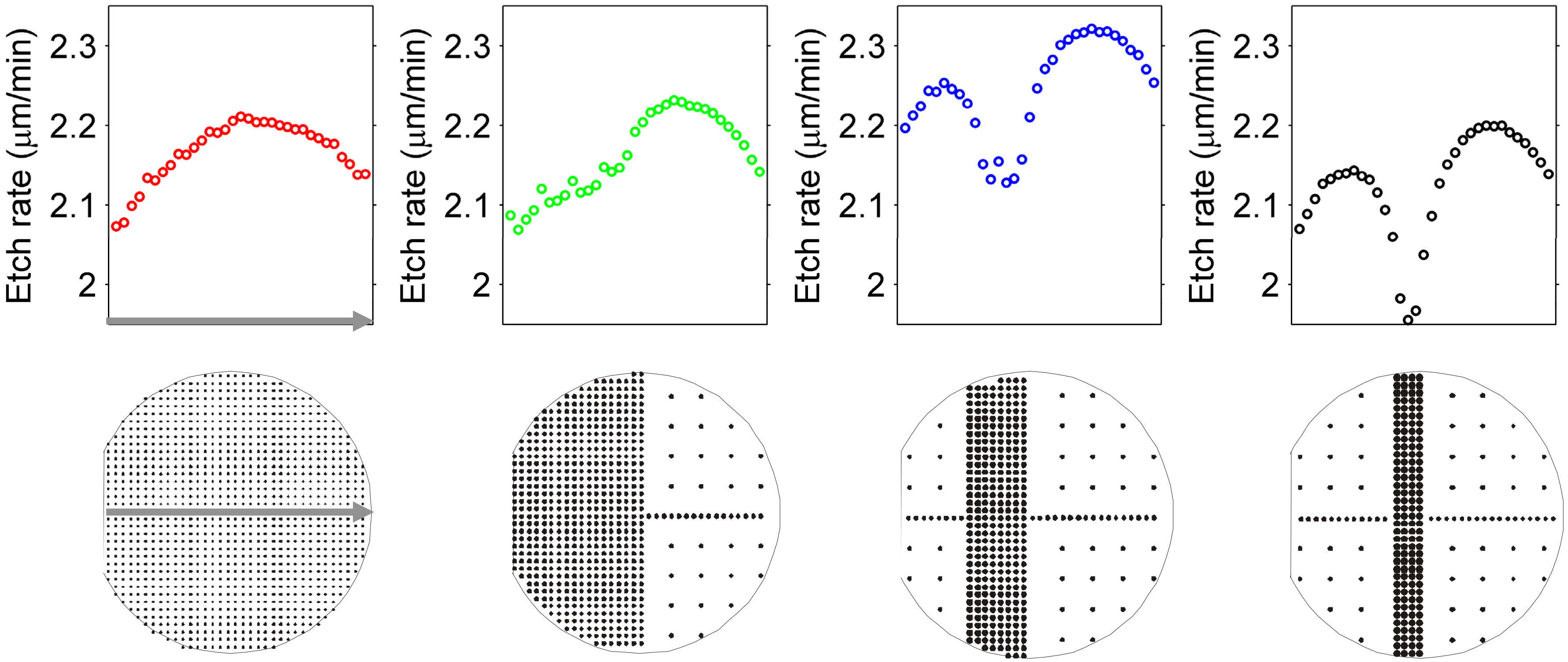
competition for reactants; diffusion

wafer/chamber-scale

ion and radical flux distribution

wafer-level ‘loading’

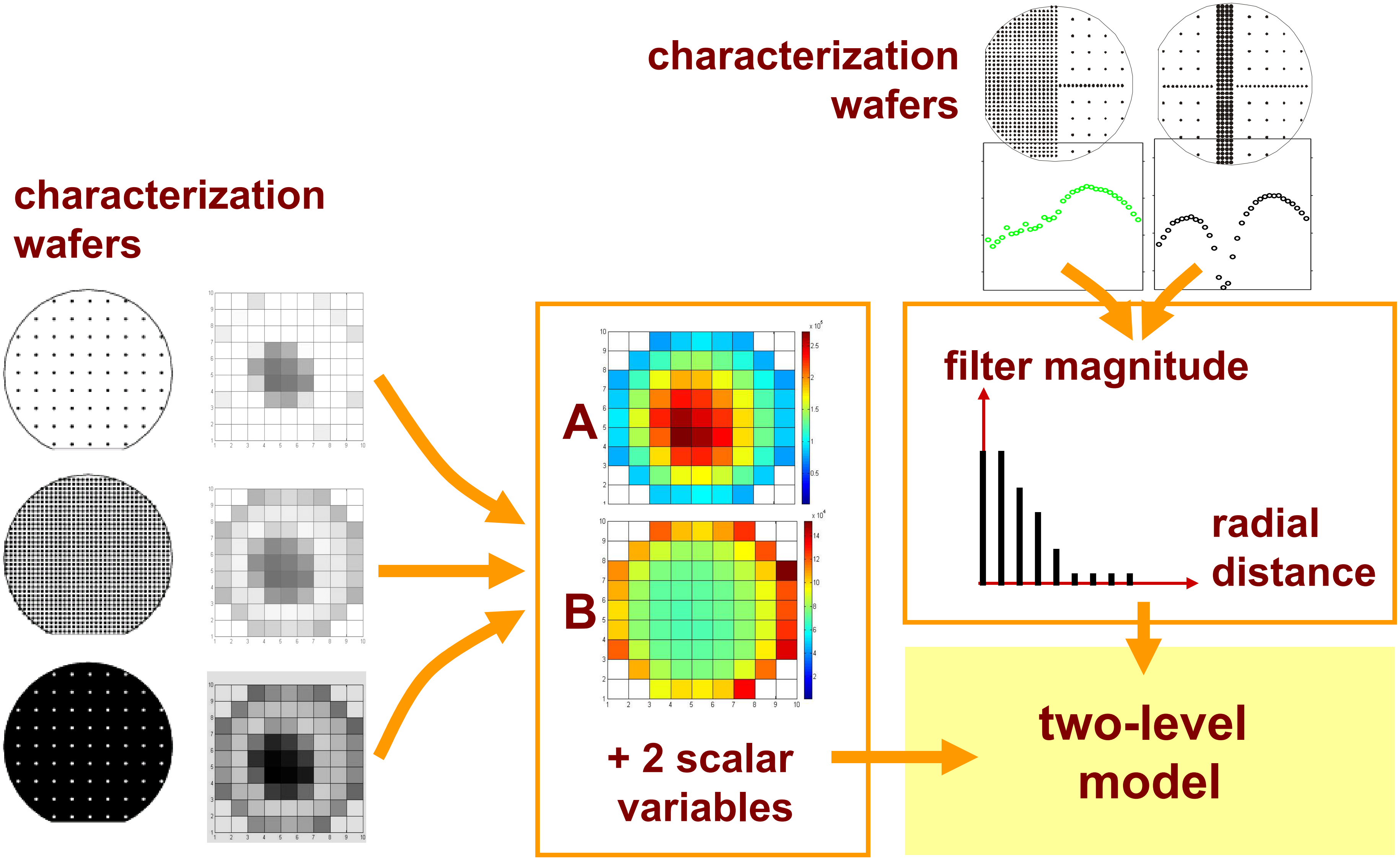
Previously observed pattern-dependent variation



Average pattern density 5% throughout
Localized to differing extents

H.K. Taylor *et al.*, submitted for publication

A two-level model, tuned for each tool + recipe



characterization
wafers

characterization
wafers

+ 2 scalar
variables

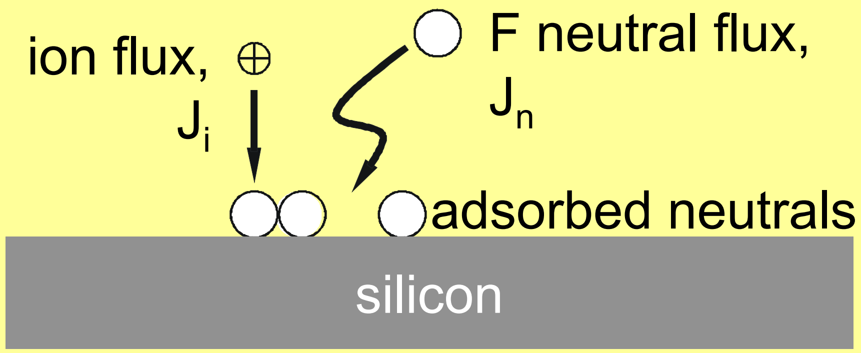
filter magnitude

radial
distance

two-level
model

H. Sun *et al.*, Proc. MEMS 05 + work submitted for publication

Basis for chamber-scale model?

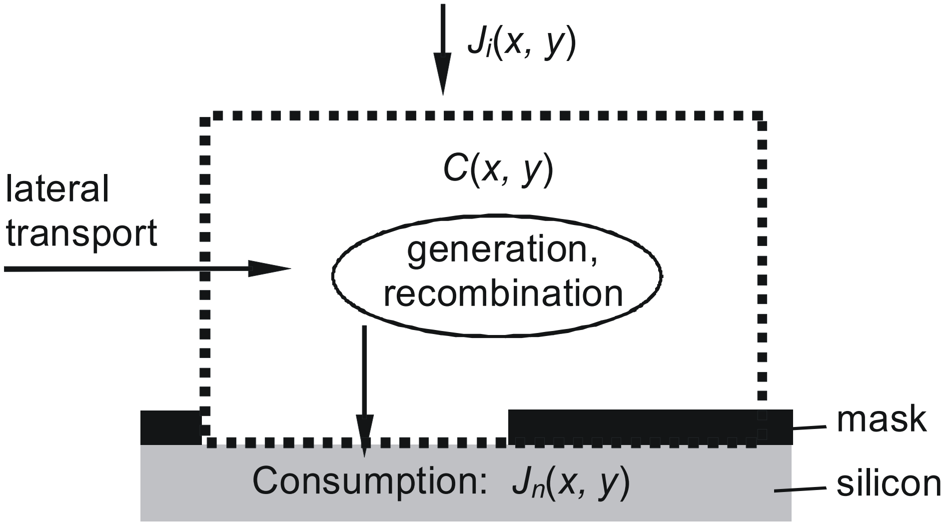


R: etch rate
Θ: surface coverage
kE_i: activity constant for ions
vS_0: activity constant for radicals

$$R = k\Theta E_i J_i$$

$$R = vS_0(1-\Theta)J_n$$

$$\frac{1}{R} = \frac{1}{kE_iJ_i} + \frac{1}{vS_0J_n}$$

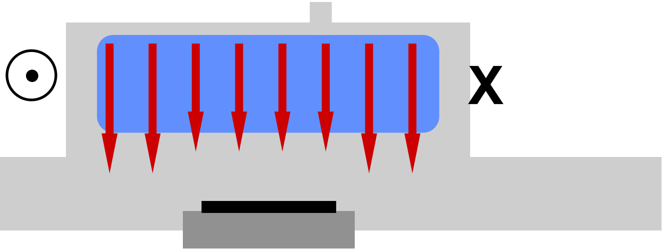


C: fluorine concentration
G: fluorine generation rate
ρ: wafer-average pattern density

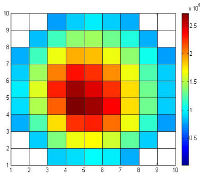
$$C = \frac{G\tau}{\underset{\uparrow\atop\text{rate ct.}}{\underline{\alpha_1\tau}}\left[\rho + \underset{\uparrow\atop\text{selectivity}}{\alpha_2}\left(1-\underset{\uparrow\atop\text{'loading'}}{\rho}\right)\right]+1}$$

Synergism model: Gottscho *et al.*, *J Vac Sci Tech B* **10** 2133 (1992).
Right: H.K. Taylor *et al.*, submitted for publication

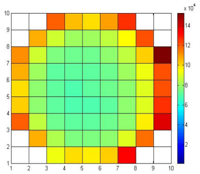
Basis for chamber-scale model?



$A, \propto J_i$



$B, \propto G_n$



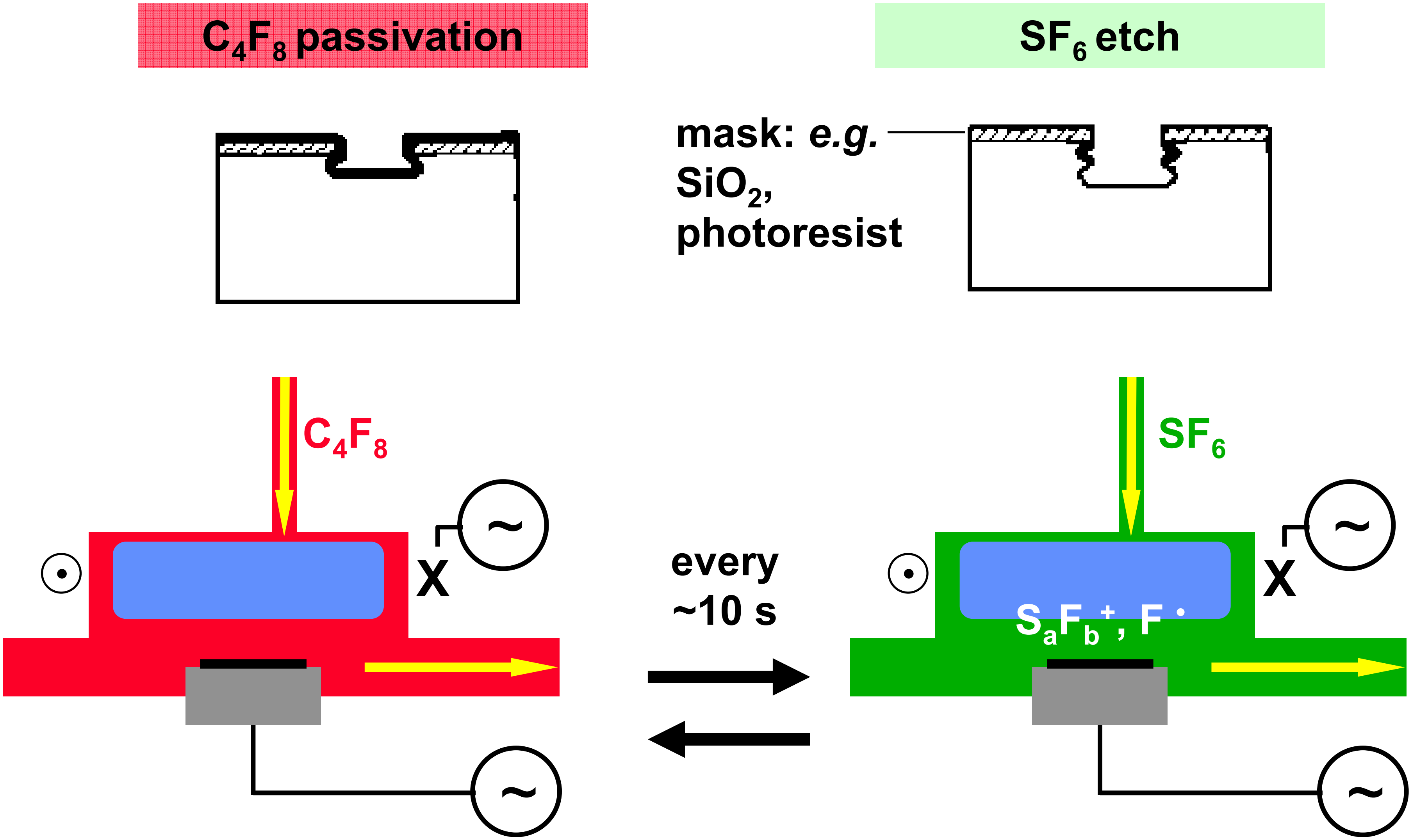
+ 2 scalar variables

Assuming:

- ion flux independent of etched pattern
- F generation (G) independent of etched pattern
- neutral flux (J_n) ∝ F concentration
- F concentration depleted as loading increases
- F concentration depends on G

H.K. Taylor *et al.*, submitted for publication

Time-multiplexed ‘Bosch’ processing



C_4F_8 passivation

SF_6 etch

mask: *e.g.* SiO_2, photoresist

every ~10 s

Journal of The Electrochemical Society, 146 (1) 339-349 (1999);
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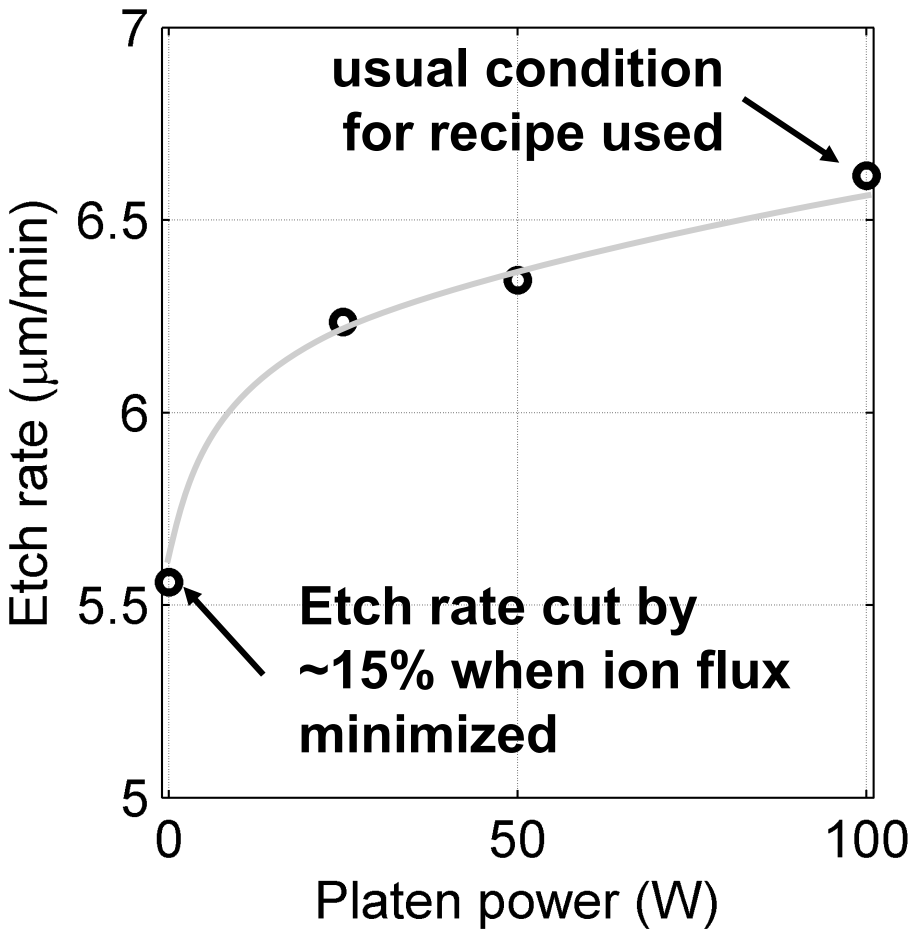
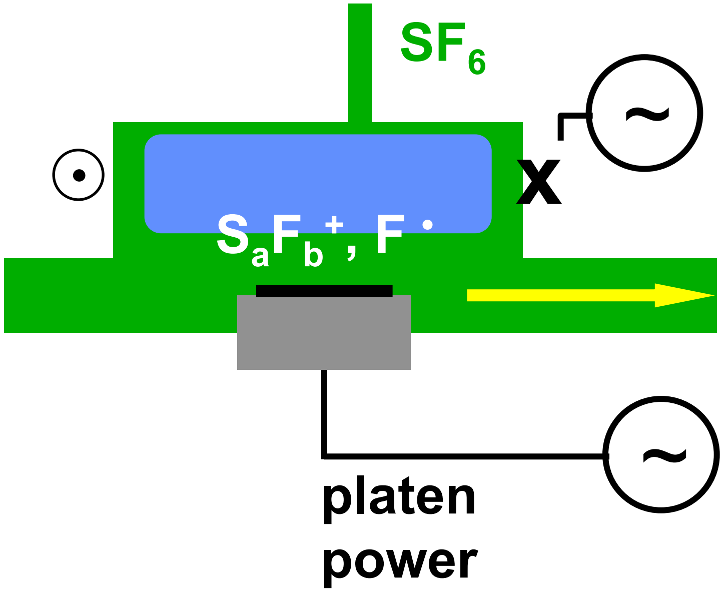
Accounting for spontaneity in Si etching

5' SF_6 etch with no passivation steps

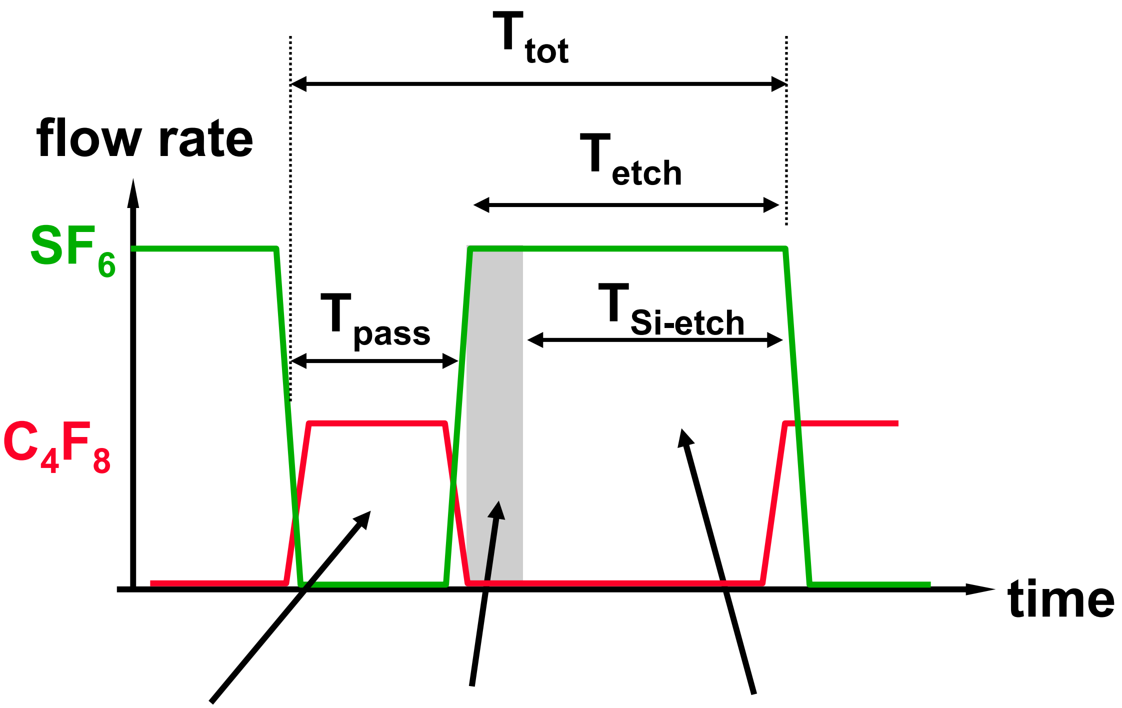




But **spontaneous etching is readily incorporated into map A:**

$$R = \Theta\left(kE_i J_i + c\right)$$
$$R = vS_0\left(1-\Theta\right)J_n$$

Accounting for time-multiplexing



Non-uniformity of CF_x flux may matter

Ion flux definitely important (T_{strip})

Ion flux important to an extent ($T_{Si\text{-}etch}$)

Time-multiplexing model

R_{Si} is the etch rate our previous model would have predicted.
Overall, modified rate prediction:

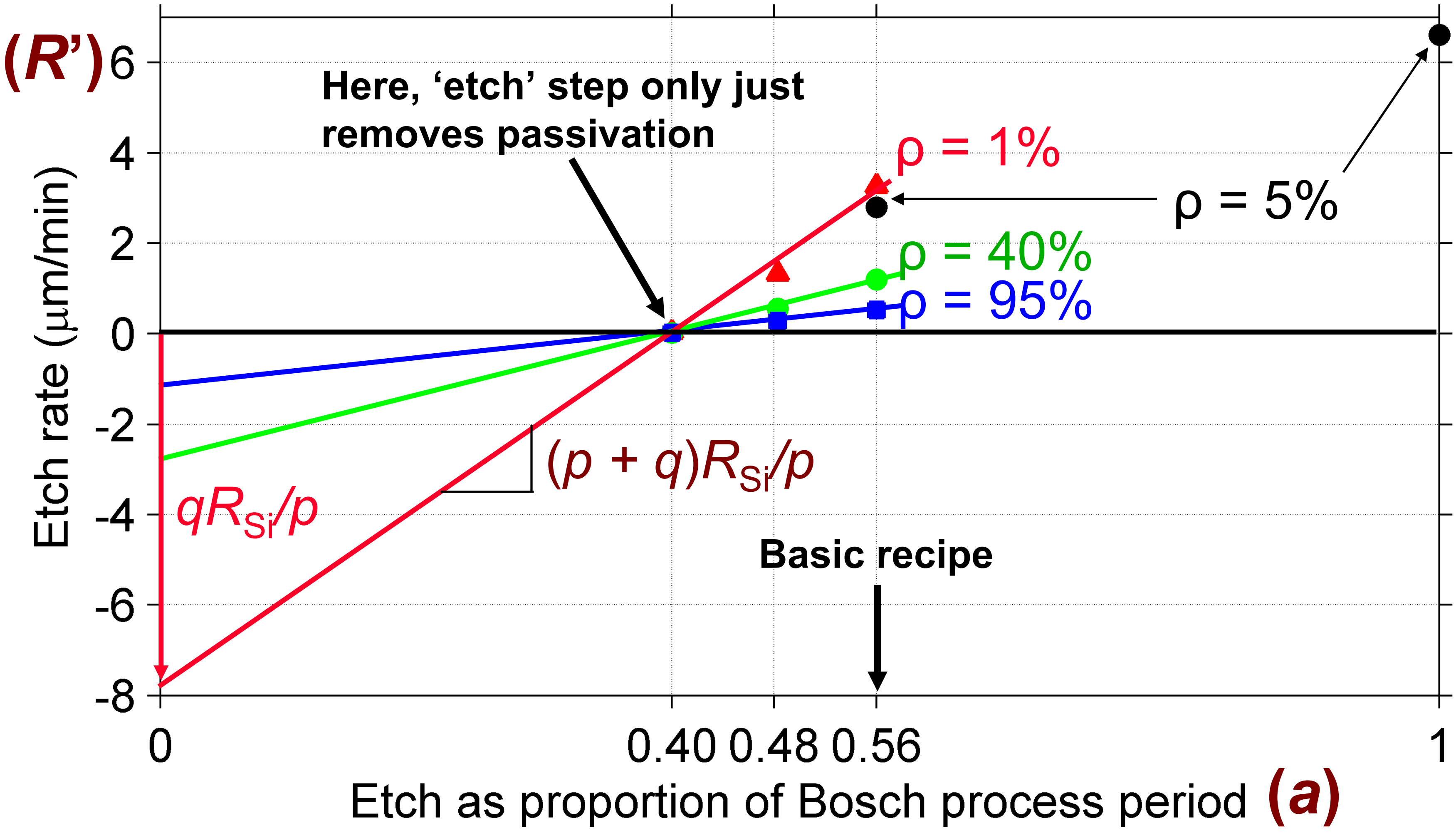
$$R' = \frac{T_{Si-etch} R_{Si}}{T_{tot}} = \frac{R_{Si}\left(T_{etch} - T_{strip}\right)}{T_{tot}} = \frac{R_{Si}\left(T_{etch} - \dfrac{T_{pass} k_{pass} J_{CF_x}}{J_i k_{strip}}\right)}{T_{tot}}$$

If we define $a = T_{etch}/T_{tot}$, $p = J_i k_{strip}$, $q = k_{pass} J_{CFx}$, we have:

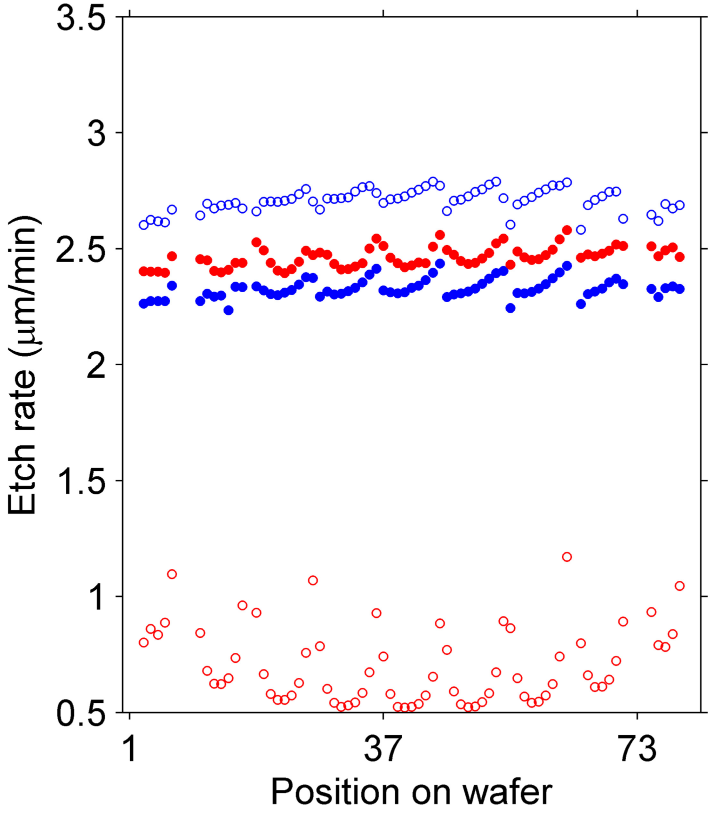
$$R' = \frac{\left[a\left(p+q\right) - q\right] R_{Si}}{p}$$

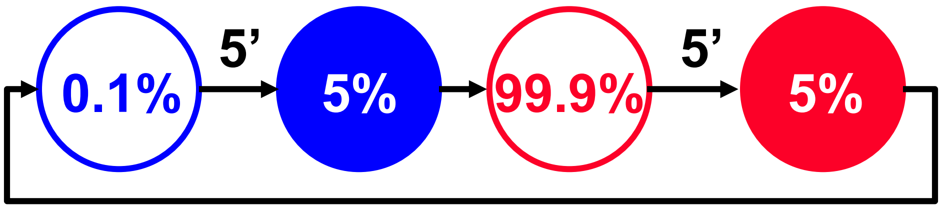
$R' = ma + c$ with $m = (p + q)R_{Si}/p$ and $c = -qR_{Si}/p$.

Rate of passivation removal



(Short-term) memory effect in chamber





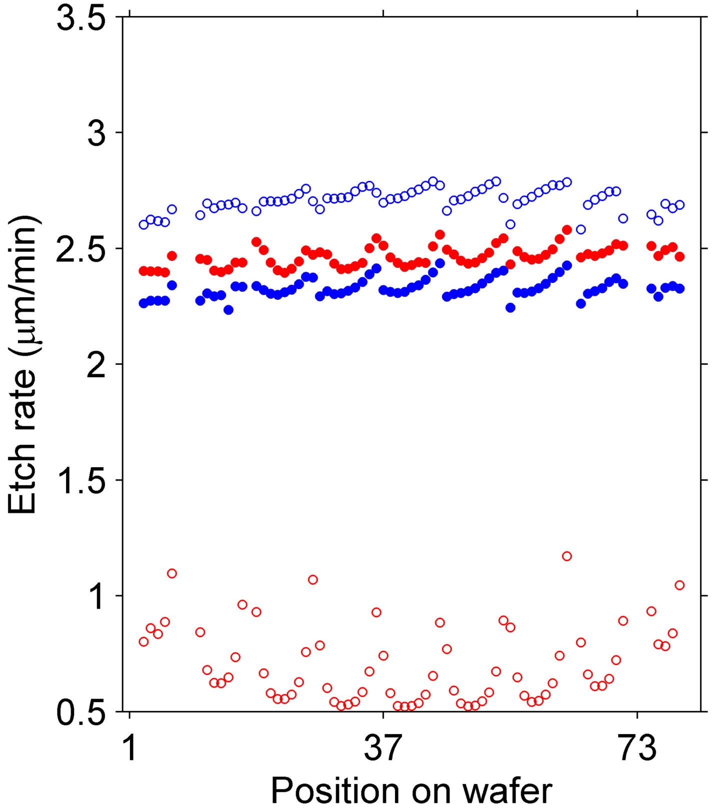
several cycles

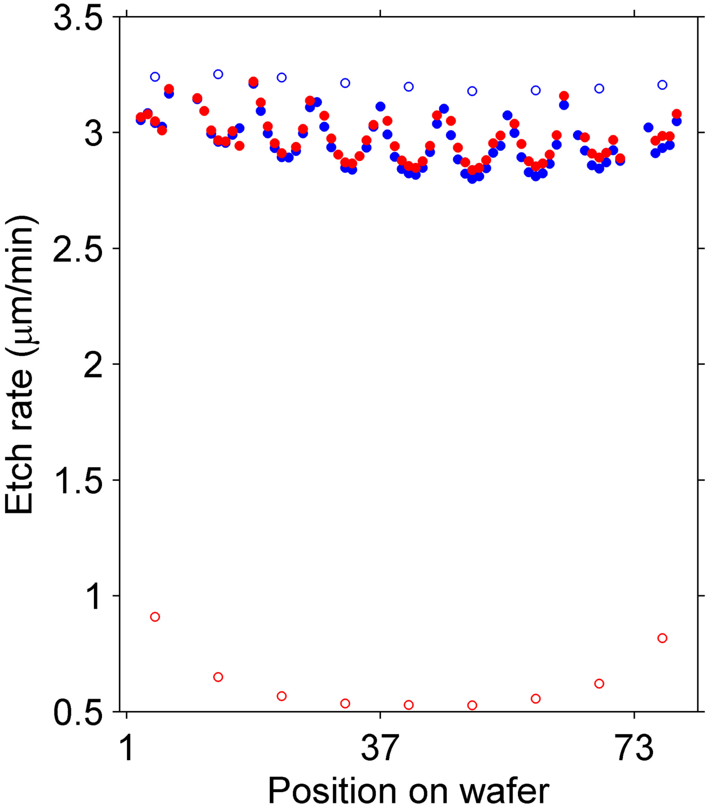
Thermal diffusivity of aluminum ~ 10^{-4} m^2/s

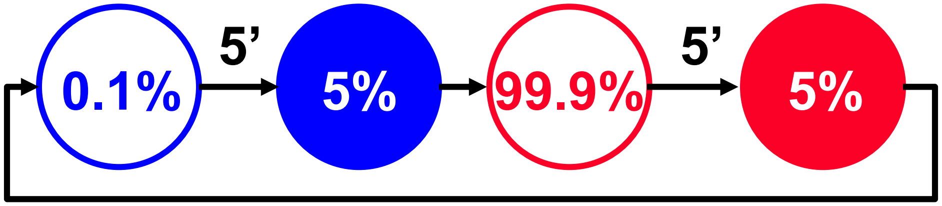
Over 5', characteristic length ~0.17 m

Over 30', characteristic length ~0.42 m

(Short-term) memory effect in chamber

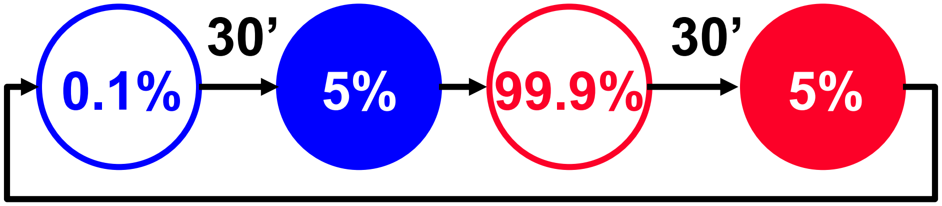






0.1% → 5' → 5% → 99.9% → 5' → 5%

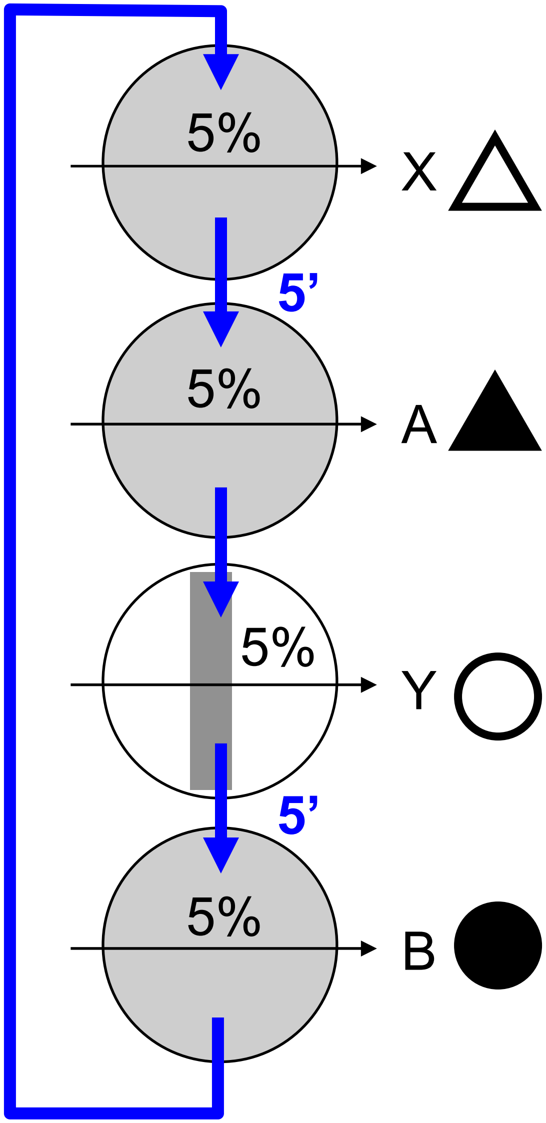
several cycles

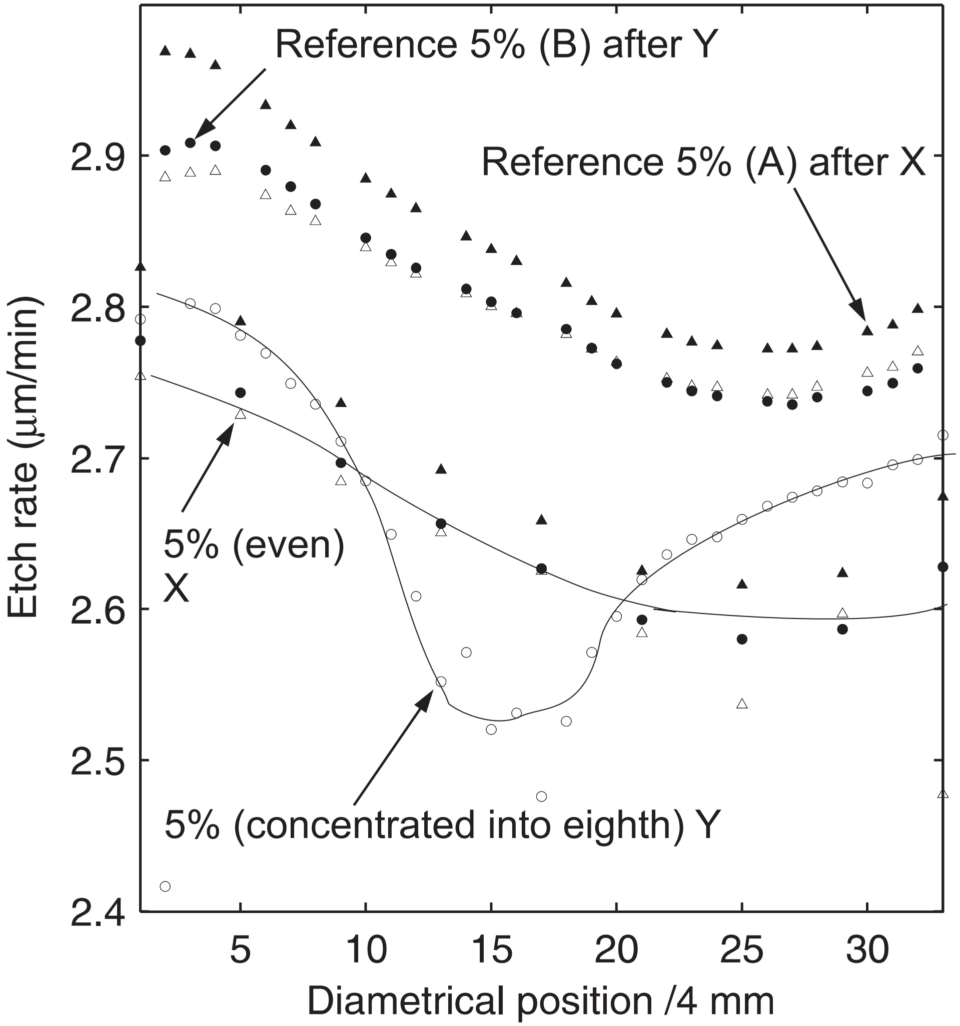


0.1% → 30' → 5% → 99.9% → 30' → 5%

several cycles

Pattern component of memory effect?





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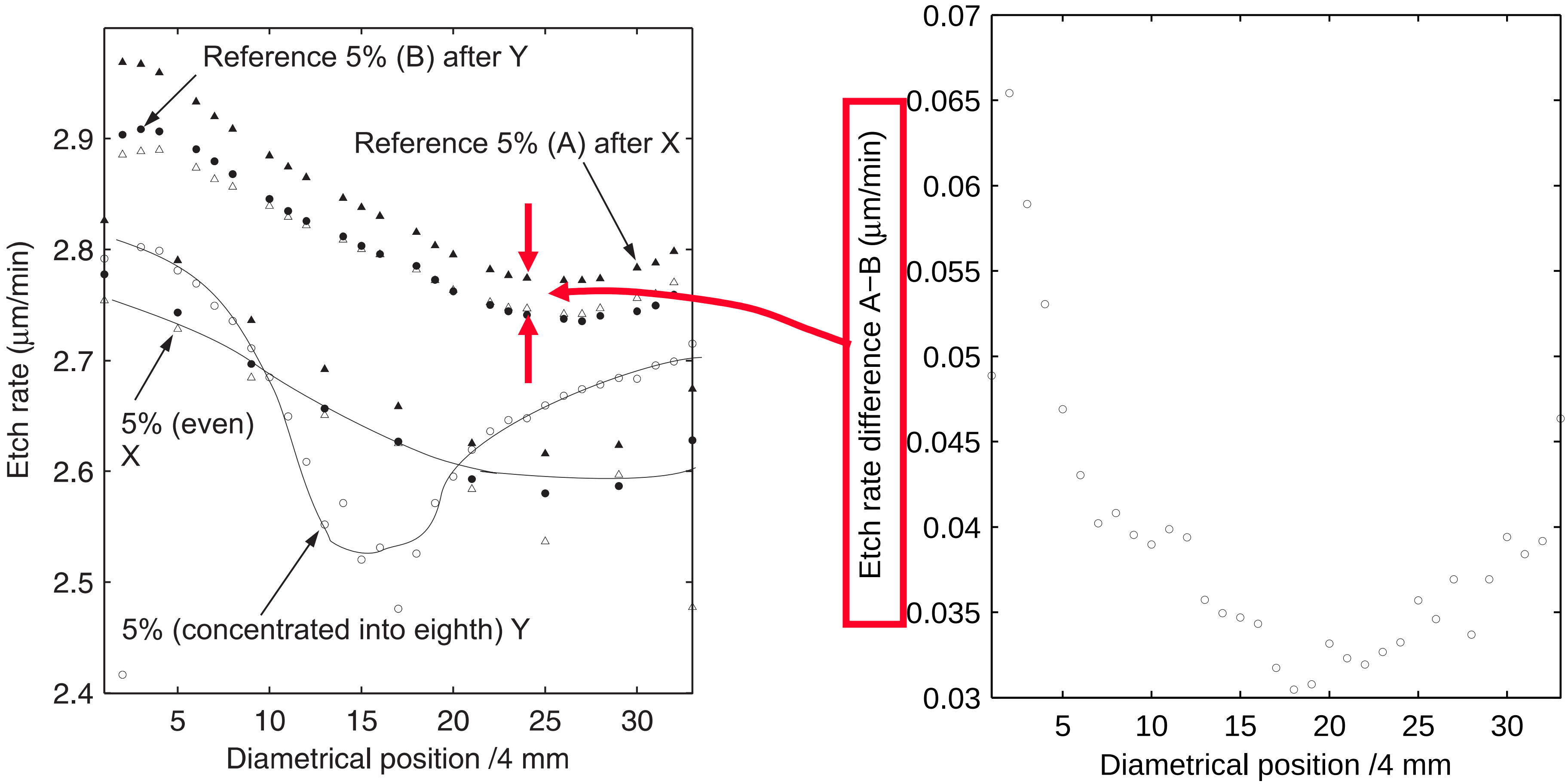
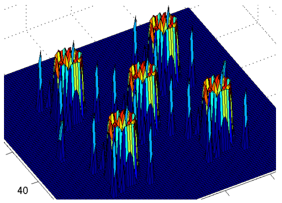
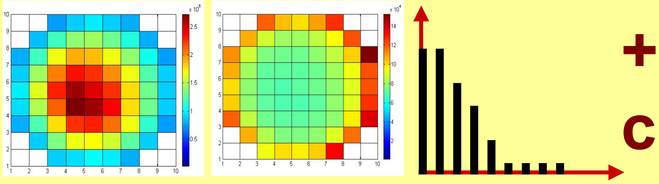


Putting two-level model into action

discretized mask design

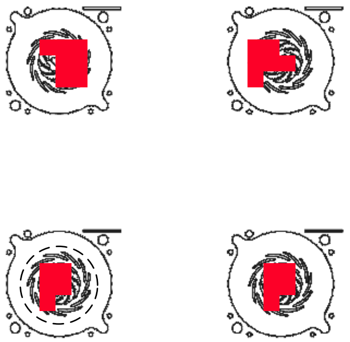




+ scalar constants

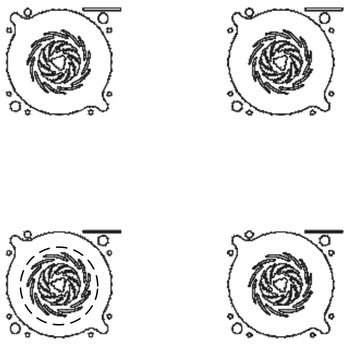
two-level model
takes a few seconds to run

highlight problems on-screen

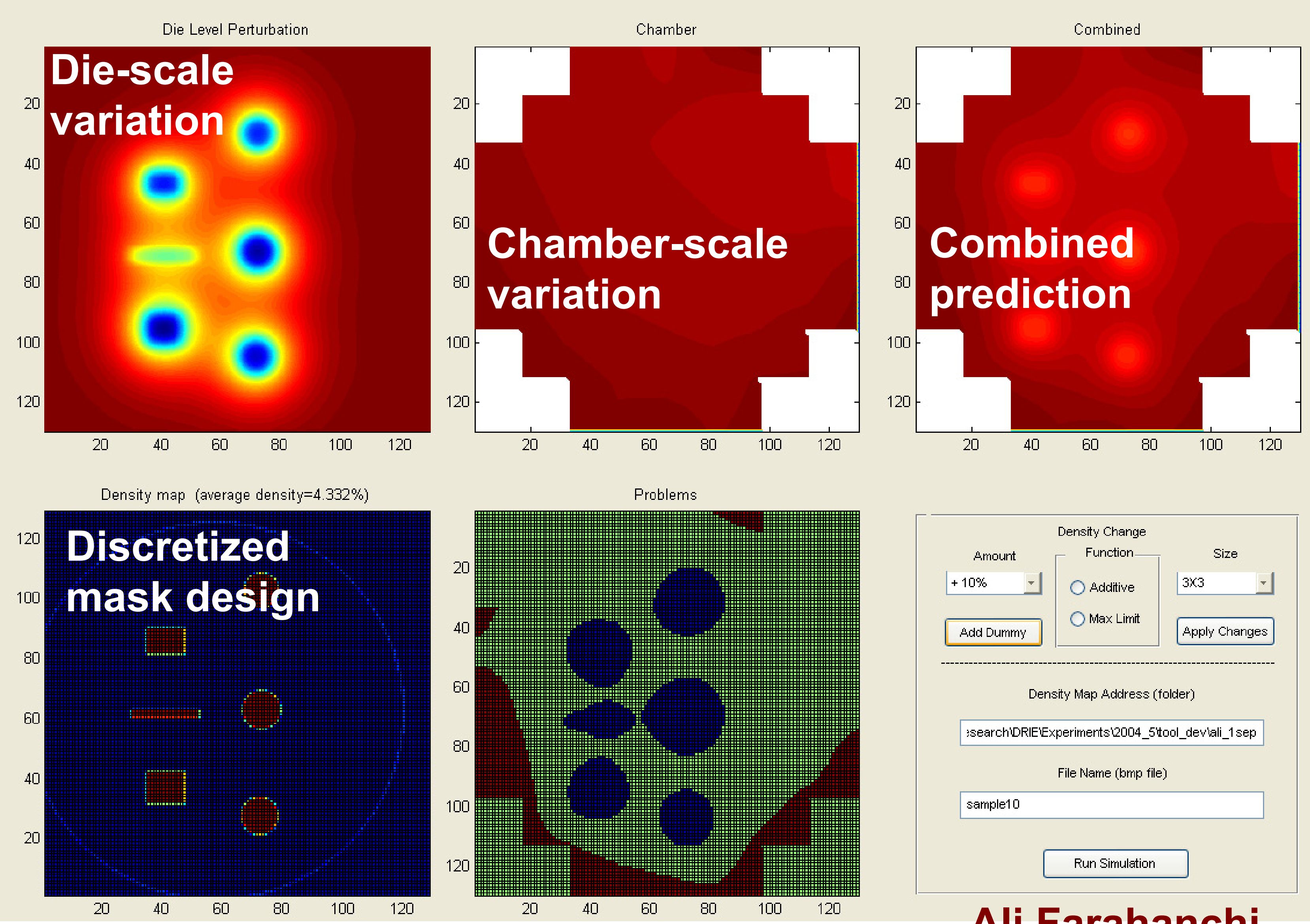


refine mask design

drafting software



CAD tool for nonuniformity prediction



Die-scale variation

Chamber-scale variation

Combined prediction

Discretized mask design

Amount: + 10%

Function: ○ Additive ○ Max Limit

Size: 3X3

Density Map Address (folder): :search\DRIE\Experiments\2004_5\tool_dev\ali_1sep

File Name (bmp file): sample10

Ali Farahanchi

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