# Extraction of Planarization Length and Response Function in Chemical-Mechanical Polishing

*MRS 1998*

*Symposium Q: Materials Issues in Chemical-Mechanical Polishing*

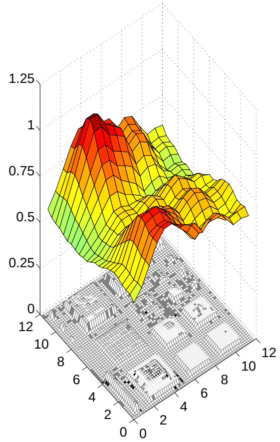
*Invited Talk*

Duane Boning, Dennis Ouma, and James Chung

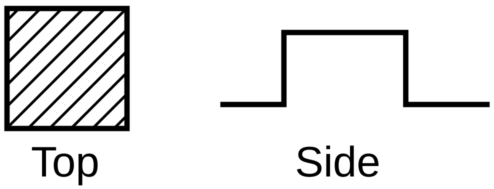
Massachusetts Institute of Technology, EECS
Microsystems Technology Laboratories
Room 39-567, Phone: (617) 253-0931
Email: boning@mtl.mit.edu

# Capsule Summary

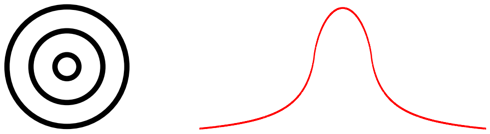
- **Problem:** Global non-planarity within die in oxide CMP



- **Goal:** Efficient modeling of oxide thickness across arbitrary product die patterns
- **Approach:** Simplified analytic model
  - ❑ Removal rate is inversely proportional to effective density
  - ❑ Effective density determination is critical:
    - polish at each point is affected by nearby topography/pattern density



- **Previous Work:** Square uniformly weighted window to calculate effective density



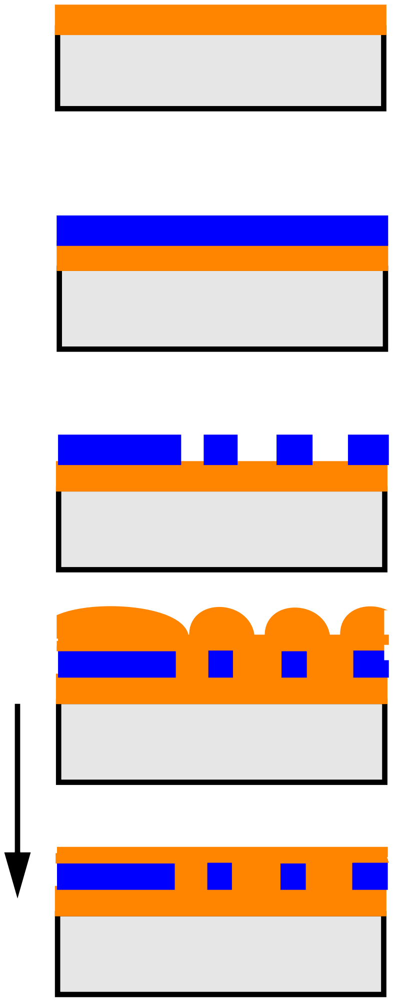
- **This Work:**
  - ❑ Circular elliptically weighted “response function” for effective density
  - ❑ Response function is physically motivated: elastic pad bending/deformation
  - ❑ New “step density” test pattern to improve extraction/characterization

# Outline

- Capsule Summary
- Background
    - Global Non-Planarity and Oxide Thickness Prediction
- Modeling
    - Density-Dependent Oxide CMP Model
    - Effective Density Calculation - **Square Window & Planarization Length**
    - Signal Processing Analogy - Density Step Response
- Physically-Motivated Effective Density Calculation
    - **Elliptic Window & Planarization Response Function**
- Results
    - Density Step Test Structure
- Discussion and Summary

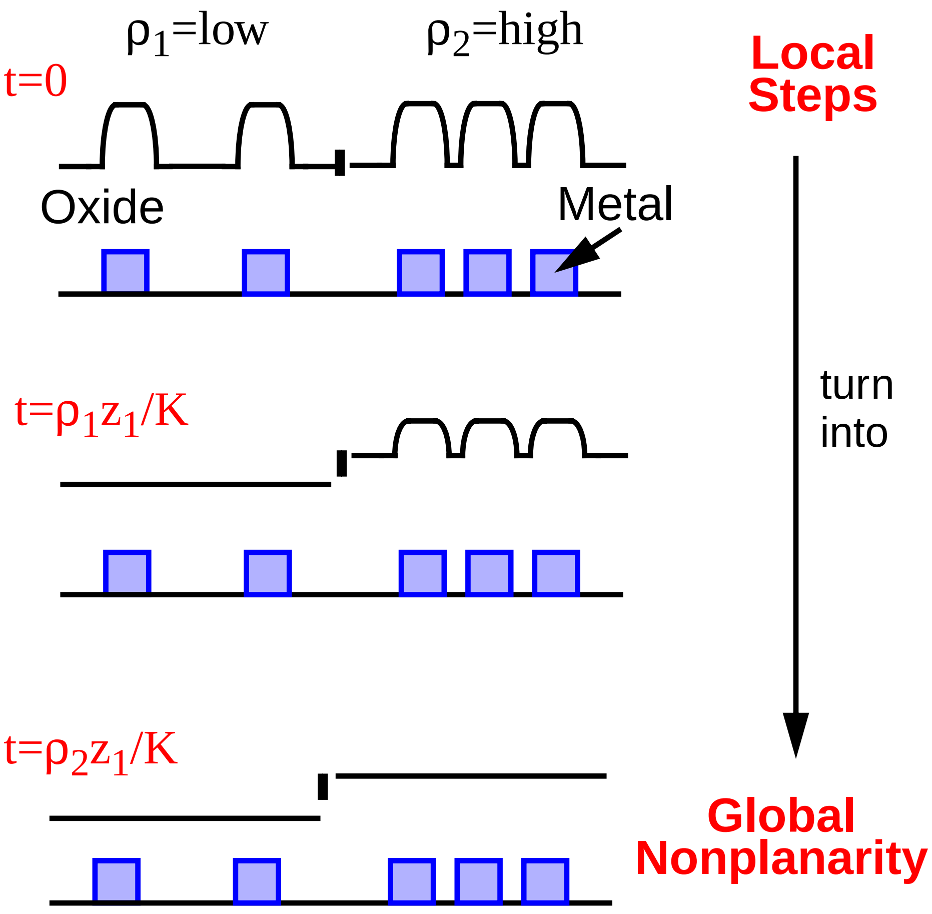
# Problem: Oxide Thickness Variation & CMP

## Goal:



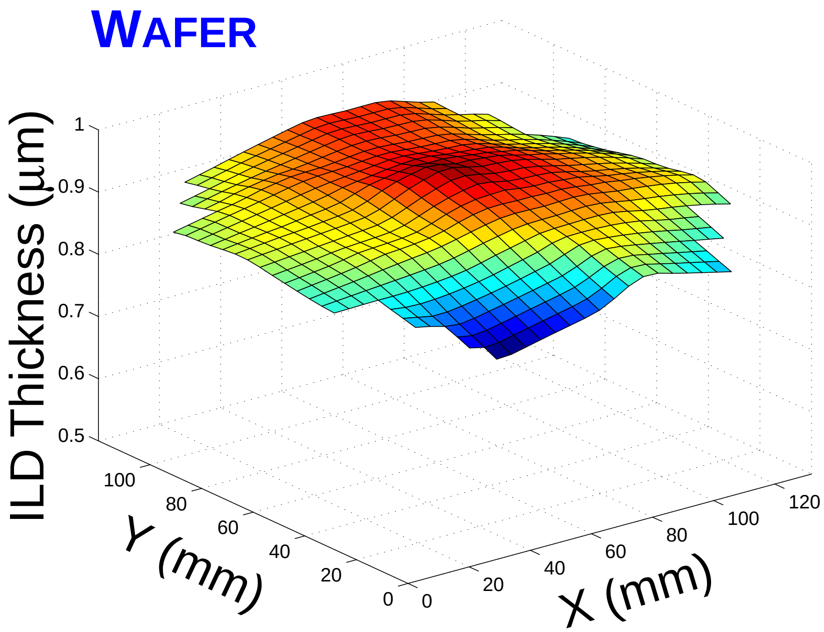
Chemical-Mechanical Polishing to remove local step

## Reality:

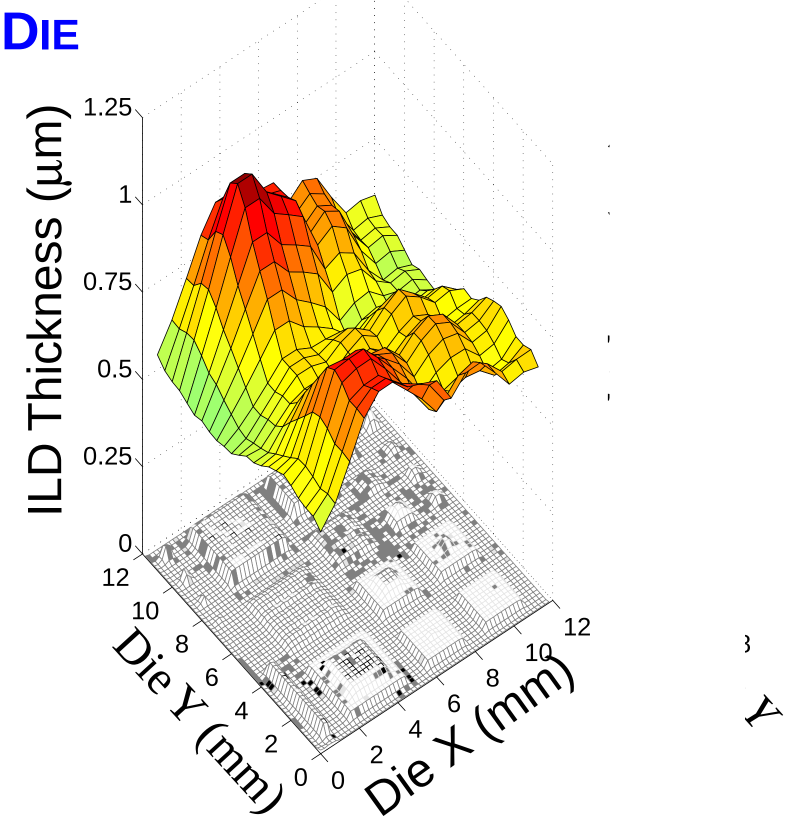


# Goal: Die-Level Prediction of Oxide Thickness

- InterLevel Dielectric (ILD) thickness varies across both the wafer and across each die


WAFER

- The variation within the die is often larger than the across-wafer variation
- Each product/layer produces a unique die-level variation pattern and thickness range


DIE

# Oxide CMP Model: Previous Work

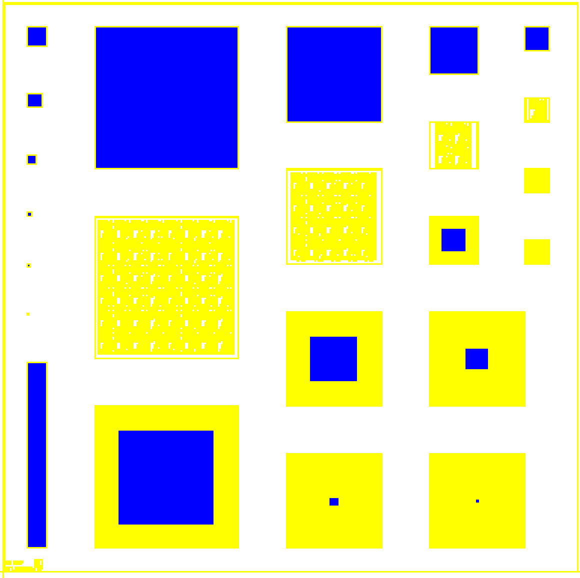
- CMP Characterization Mask Set
  - Pitch (linewidth and line space), perimeter, and structure area are **minor** effects
  - Conclusion: **Density** is the key layout parameter
  - Observe a simple oxide thickness vs. density dependence!

- Oxide CMP Global Planarization Model

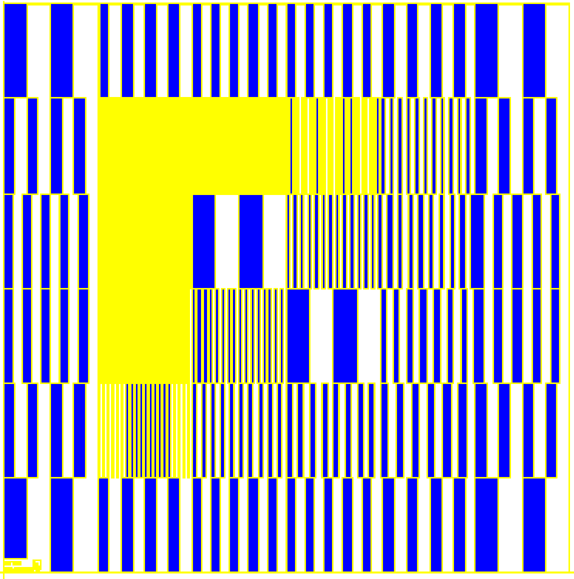
1. Polish rate at each point on the die is inversely proportional to the effective pattern density
2. Effective pattern density at each point depends on the nearby topography and density
3. The effective pattern density can be determined by the planarization window (or planarization length)
4. The planarization length must be characterized for a given CMP consumable set and process

# MIT/Sandia/HP CMP Test Masks

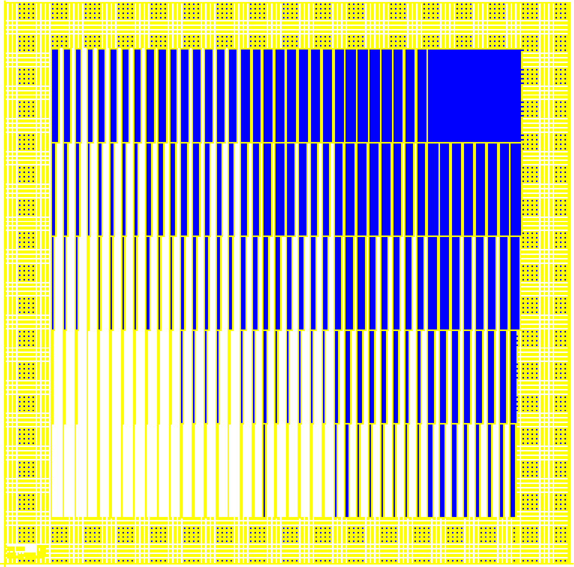
- What are the key effects?
- Extraction of key model parameters



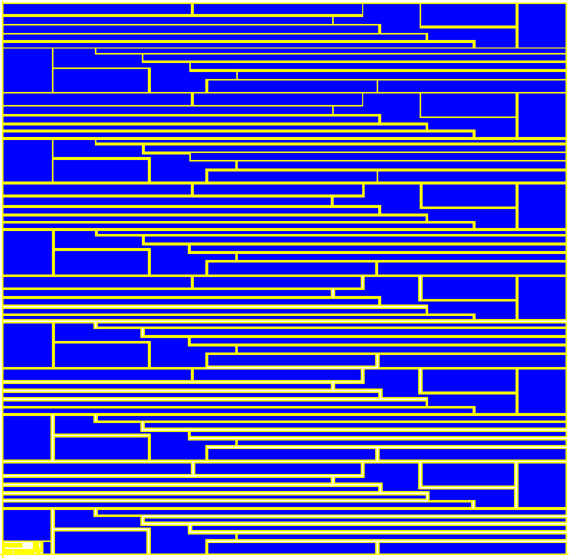
**Area Mask**



**Pitch Mask**

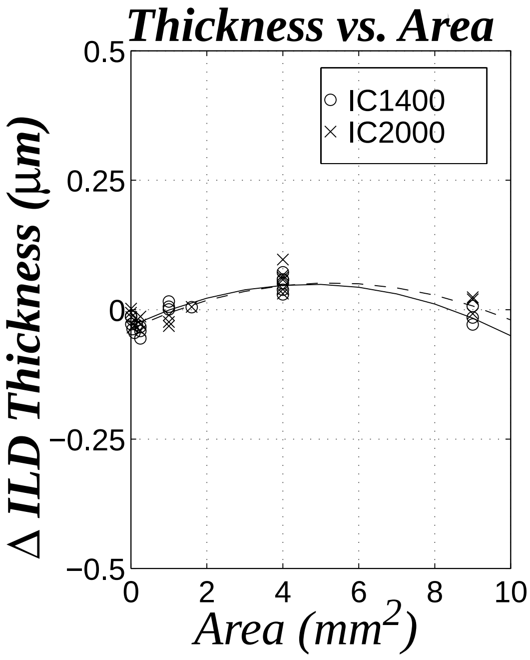


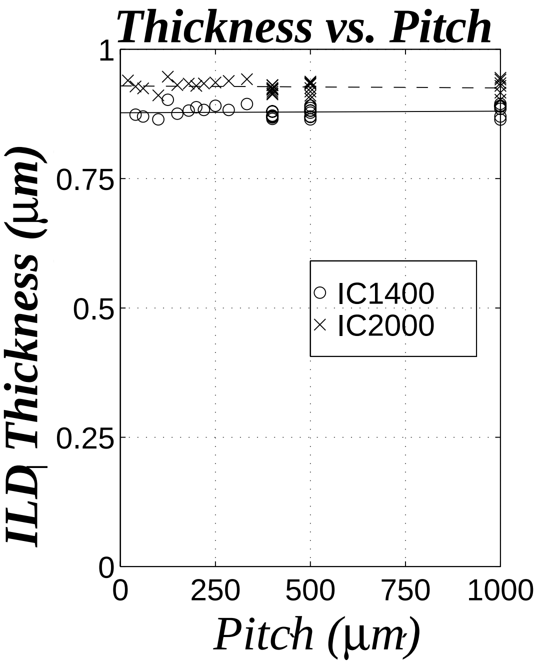
**Density Mask**

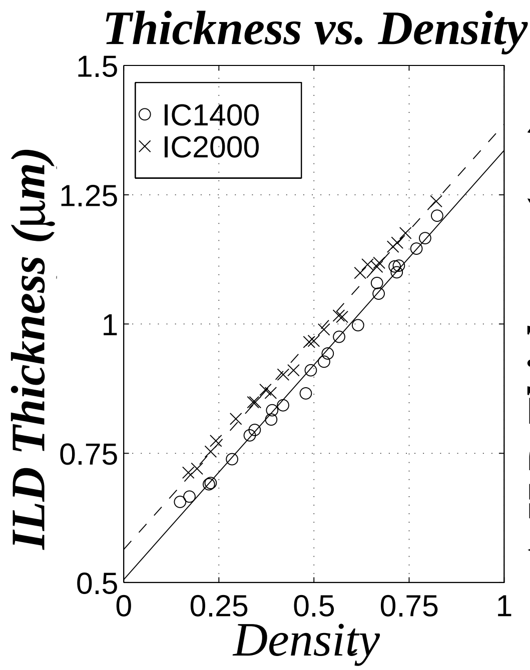


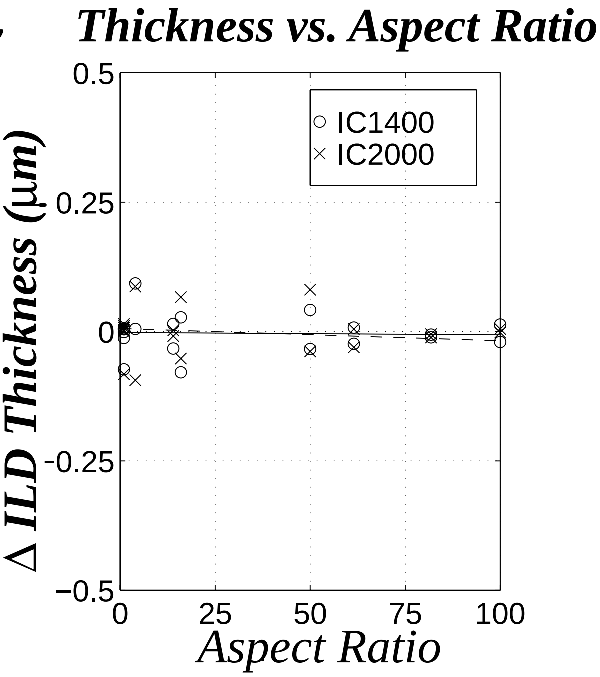
**Perimeter/Area**

# Result: Density Effect is Dominant


Thickness vs. Area


Thickness vs. Pitch


Thickness vs. Density

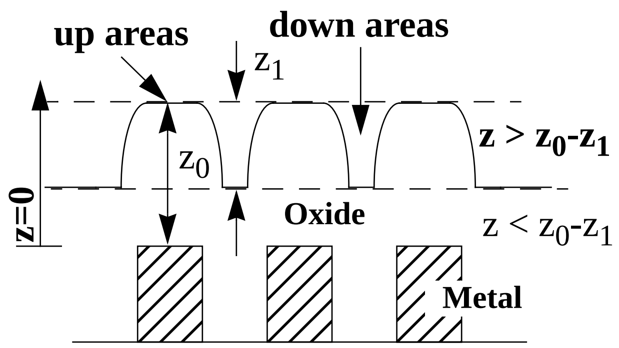

Thickness vs. Aspect Ratio

- Simple linear relationship between final oxide thickness and effective density

# Outline

- ■ Capsule Summary
- ■ Background
  - ❑ Global Non-Planarity and Oxide Thickness Prediction
- ✔ **Modeling**
  - ❑ Density-Dependent Oxide CMP Model
  - ❑ Effective Density Calculation - **Square Window & Planarization Length**
  - ❑ Signal Processing Analogy - Density Step Response
- ■ Physically-Motivated Effective Density Calculation
  - ❑ **Elliptic Window & Planarization Response Function**
- ■ Results
  - ❑ Density Step Test Structure
- ■ Discussion and Summary

# Oxide CMP Pattern Dependent Model



$z$ = final oxide thickness over metal features

$K$ = blanket oxide removal rate for a die of interest

$t$ = polish time

$\rho_0$ = local pattern density

- Removal rate inversely proportional to density:

$$\frac{dz}{dt} = -k_p p v = -\frac{K}{\rho(x, y)}$$

- Density assumed constant (equal to pattern) until local step has been removed:

$$\rho(x, y, z) = \begin{cases} \rho_0(x, y) & z > z_0 - z_1 \\ 1 & z < z_0 - z_1 \end{cases}$$

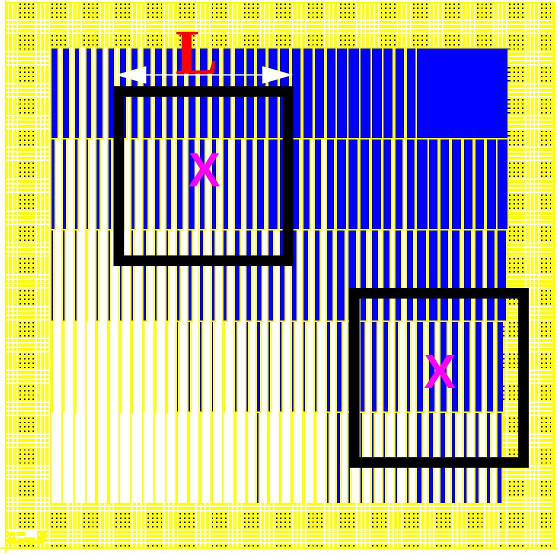
- Final oxide thickness related to effective density:

$$z = \begin{cases} z_0 - \left(\dfrac{Kt}{\rho_0(x, y)}\right) & Kt < \rho_0 z_1 \\ z_0 - z_1 - Kt + \rho_0(x, y) z_1 & Kt > \rho_0 z_1 \end{cases}$$

- Evaluation of pattern density $\rho_0(x, y)$ is key to model development!

# Effective Density Using a Moving Window

**Top view
of an example
layout**



- Effective density at X for a square constant weight window is:

$$\frac{\text{Raised area in square}}{\text{Total area of square}}$$

  - ❑ L is defined as planarization length

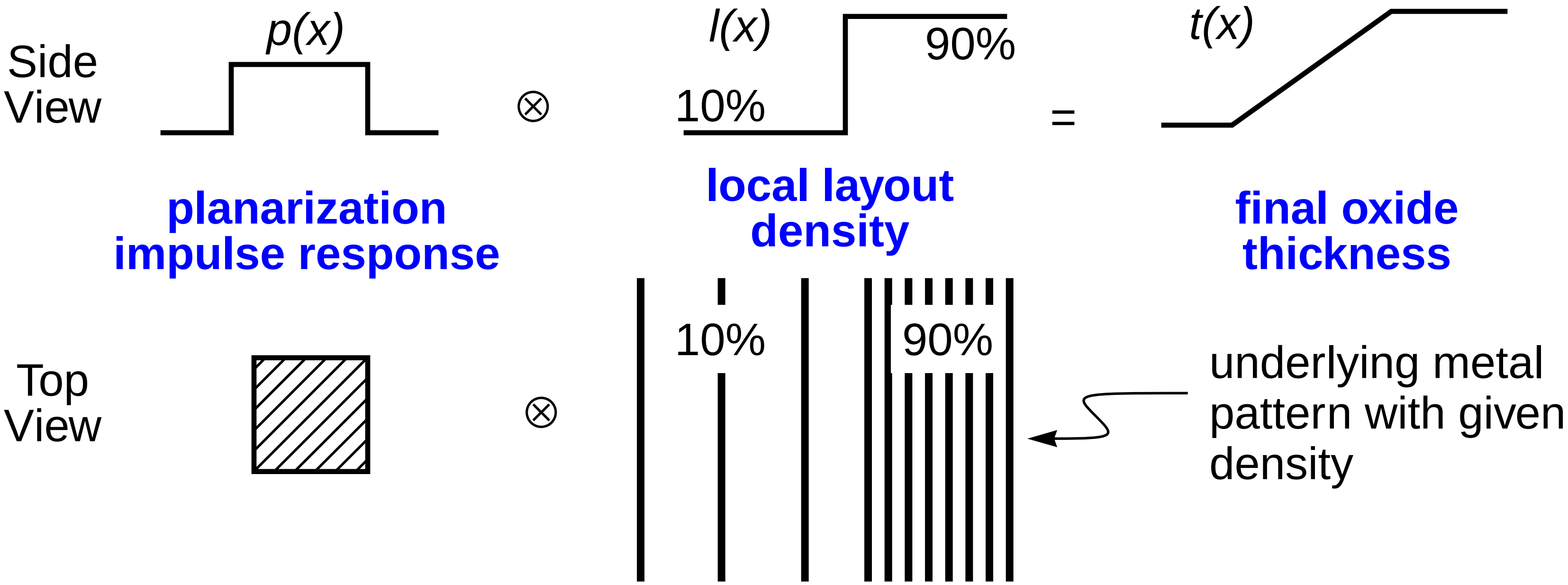
- The long-range "moving average" density calculation corresponds to a simple convolution picture:

$$d(x, y) = p(x, y) \otimes l(x, y)$$

  - ❑ *d(x,y)* is the effective density at (x,y)
  - ❑ *p(x,y)* is the "planarization impulse response" (weighting function) to raised features
  - ❑ *l(x,y)* is the local (feature-scale) density

# Signal Processing Analogy: Step & Impulse “Planarization Response”

- **Effective Density Window IDENTICAL TO “Planarization Impulse Response”**
  - Density window captures what nearby topography the pad “sees” at point X.
- Alternative to gradual density layout: Fabricate a layout “step density”
  - The resulting oxide thickness provides a **“step density response”** of the pad and process -- that can be measured experimentally



Side View

$p(x)$ $\otimes$ $l(x)$ 10% 90% = $t(x)$

**planarization impulse response**

**local layout density**

**final oxide thickness**

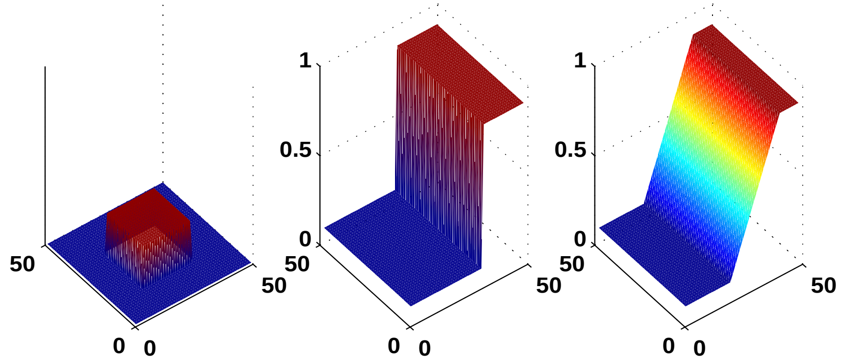
Top View

$\otimes$ 10% 90%

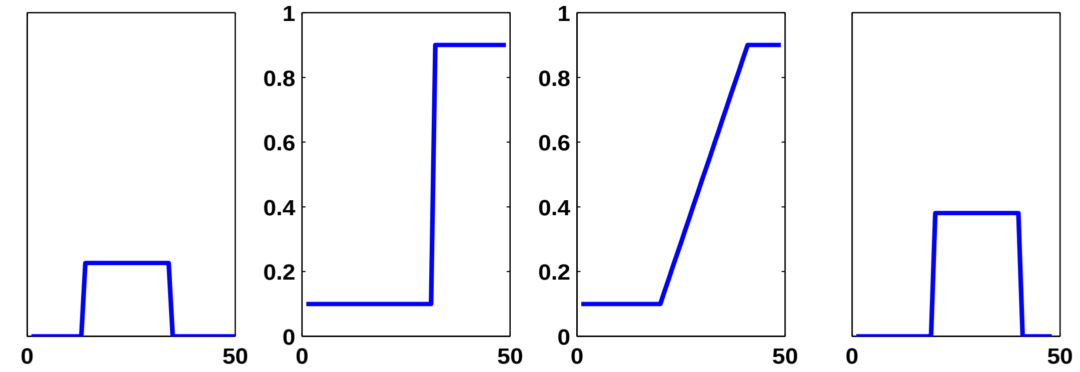
underlying metal pattern with given density

# Experimental Idea: Step Density Test Structure

2-D Step Response for Square Window



**step response**

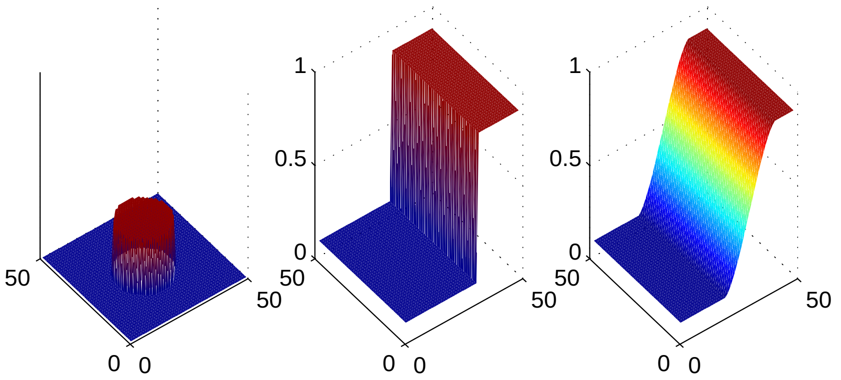


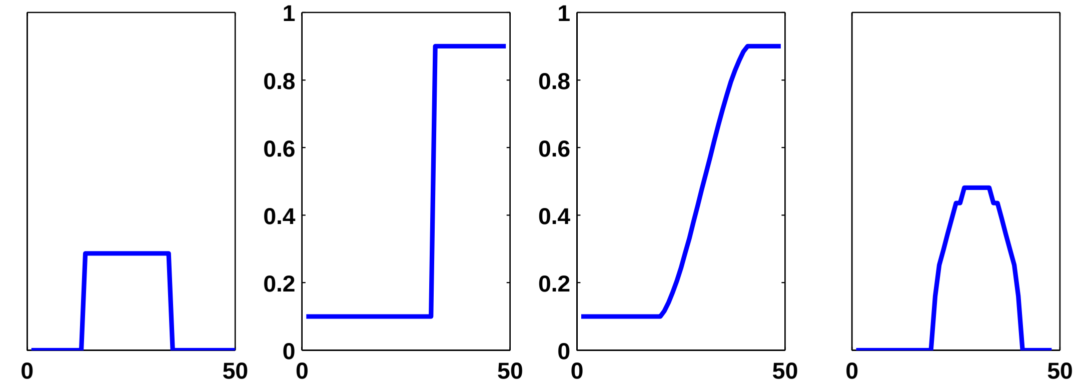
**window (impulse response)** ⊗ **local layout density** = **final oxide thickness**

**recovered window shape**

- Fabricate step density structures; polish
- Experimentally measure oxide thickness across step density structure
    - trace = “step response”
- In 1D case, can differentiate “step response” to recover the “impulse response” shape
- In 2D square window case, can also differentiate trace to recover planarization response function shape

# Planarization Step Response for Cylindrical Window

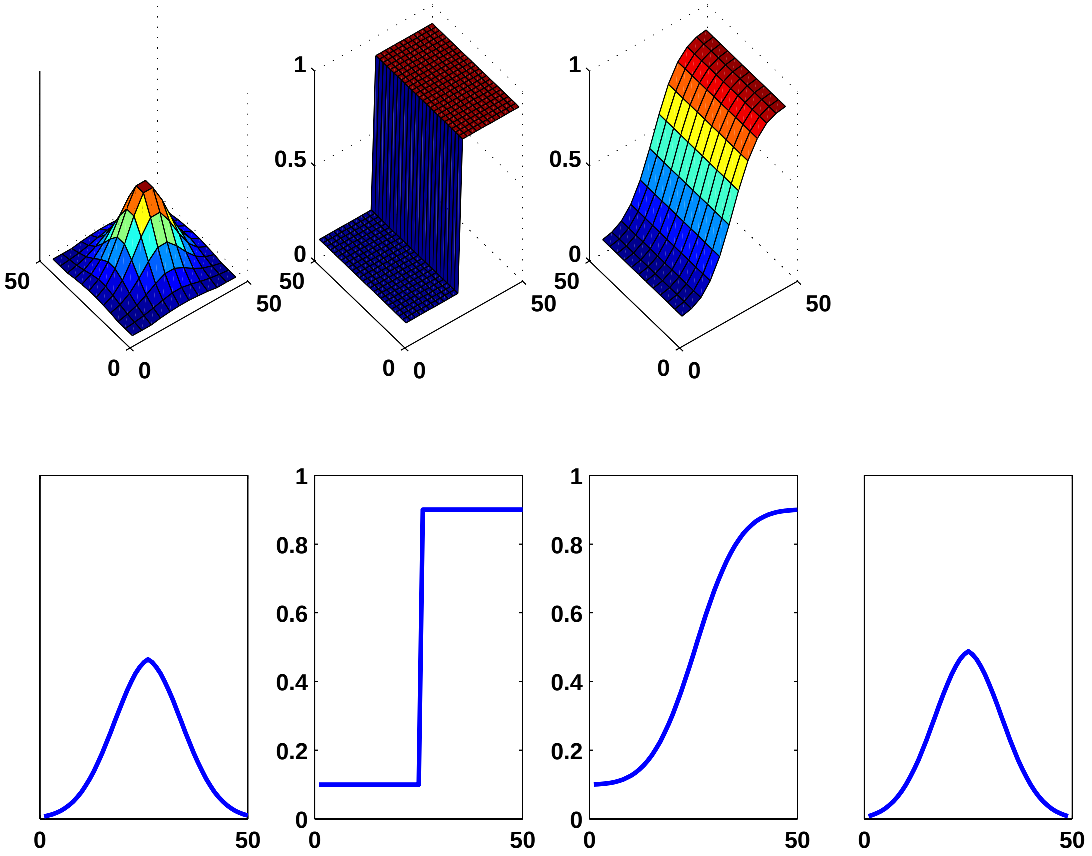




**window (impulse response)** ⊗ **local layout density** = **final oxide thickness** **recovered window shape**

- Square window is non-physical
- Consider cylindrical window
  - ❑ Radial symmetry
  - ❑ Uniform weighting
- Result: Smoother step response
- In cylindrical window case, simple differentiation of 1D trace does **NOT** correctly recover window response shape

# Planarization Step Response for Gaussian Window



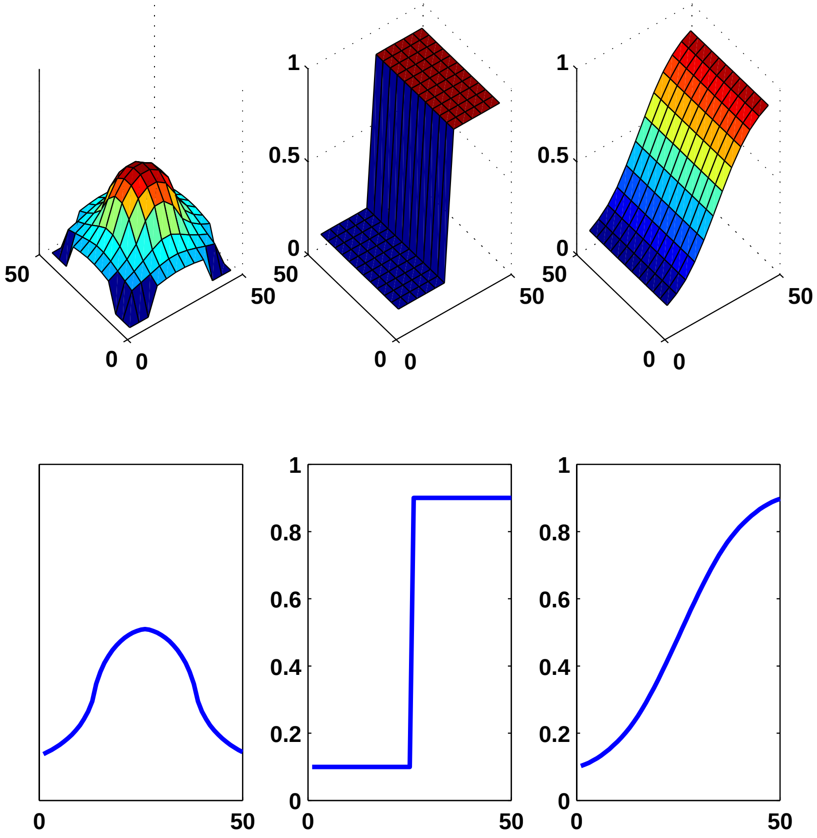
**window (impulse response)** ⊗ **local layout density** = **final oxide thickness**  **recovered window shape**

- Uniformly weighted window is non-physical
- Consider weighted circular window
  - ❑ Radial symmetry
  - ❑ Weighting depends on R
- Result: Still smoother still step response
- In gaussian window case, simple differentiation of 1D trace can correctly recover window response shape (x & y directions are separable)

# Outline

- Capsule Summary
- Background
  - ❑ Global Non-Planarity and Oxide Thickness Prediction
- Modeling
  - ❑ Density-Dependent Oxide CMP Model
  - ❑ Effective Density Calculation - **Square Window & Planarization Length**
  - ❑ Signal Processing Analogy - Density Step Response
- ✔ **Physically-Motivated Effective Density Calculation**
  - ❑ Elliptic Window & Planarization Response Function
- Results
  - ❑ Density Step Test Structure
- Discussion and Summary

# New Elliptically Weighted Planarization Response

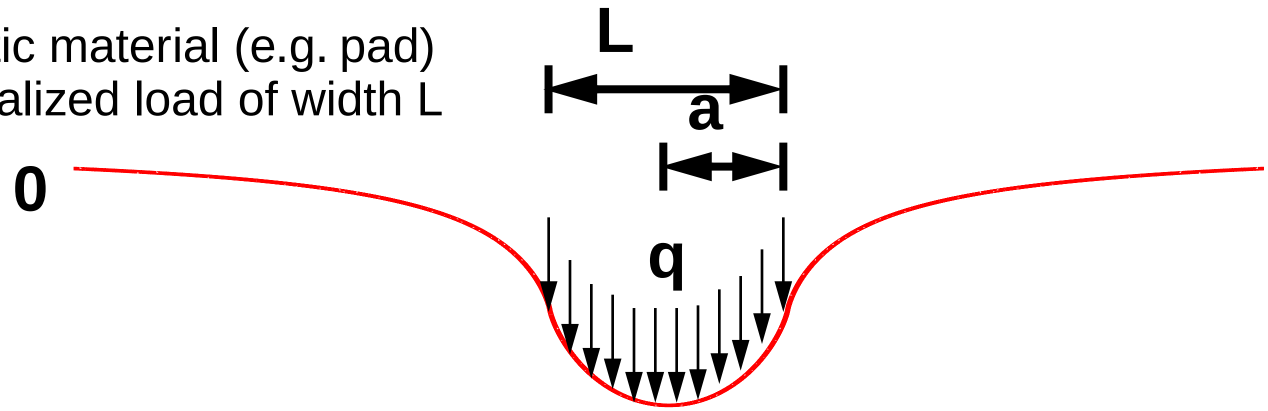


**window (impulse response)** ⊗ **local layout density** = **final oxide thickness**

- Recovering a unique window shape from the step response trace appears difficult -- assume a shape
- Question: What window shape should be used?
- Approach:
  - ❏ Find a physically sensible window
  - ❏ Tune the length scale of shape function to best match the step response (or other) experimental data
- Proposal: specially weighted window:
  - ❏ Radial symmetry
  - ❏ Weighting as an elliptic function

# Motivation: Deformation Profile in an Elastic Material

- Deformation of elastic material (e.g. pad) under a spatially localized load of width L



- Within the load area (r<a):

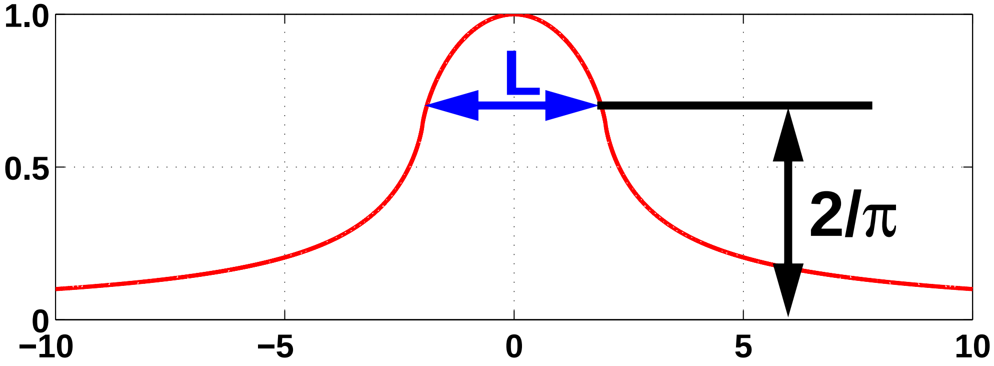
$$w(r) = \frac{4(1-v^2)qa}{\pi E}\int_0^{\frac{\pi}{2}}\sqrt{1-\frac{r^2}{a^2}\sin^2\theta}\,d\theta$$

- Outside the load area (r>a):

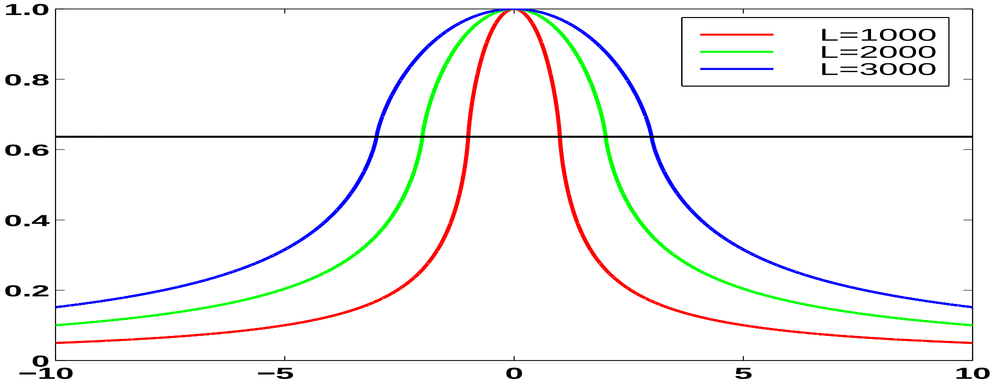
$$w(r) = \frac{4(1-v^2)qr}{\pi E}\left[\int_0^{\frac{\pi}{2}}\sqrt{1-\frac{a^2}{r^2}\sin^2\theta}\,d\theta - \left(1-\frac{a^2}{r^2}\right)\int_0^{\frac{\pi}{2}}\frac{d\theta}{\sqrt{1-\frac{a^2}{r^2}\sin^2\theta}}\right]$$

# Planarization Response Function: Length Scale Parameterization

- New Definition: “planarization length” is defined as the width (length scale) parameter in the elliptic elastic deformation function:
  - L = width of response function at $2/\pi$ of its peak value

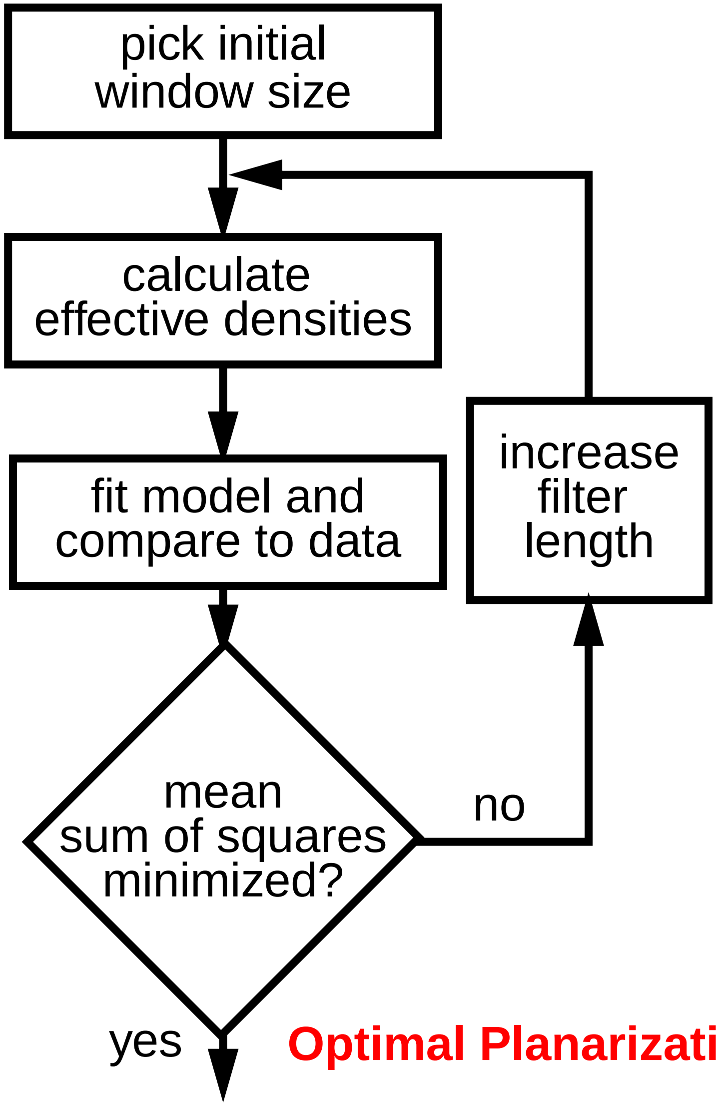


- Planarization response function
  - Shape can be varied substantial by choice of the planarization length L:
  - Use L to characterize response for given pad, process



# Experimental Extraction: Planarization Response

- Should be done for fixed process conditions
- For each candidate response function type (e.g. square, cylindrical, gaussian, elliptic)
    - ❏ Determine optimal response function length as shown on flow chart
- The response function which results in overall least mean sum of square error between model and data is chosen

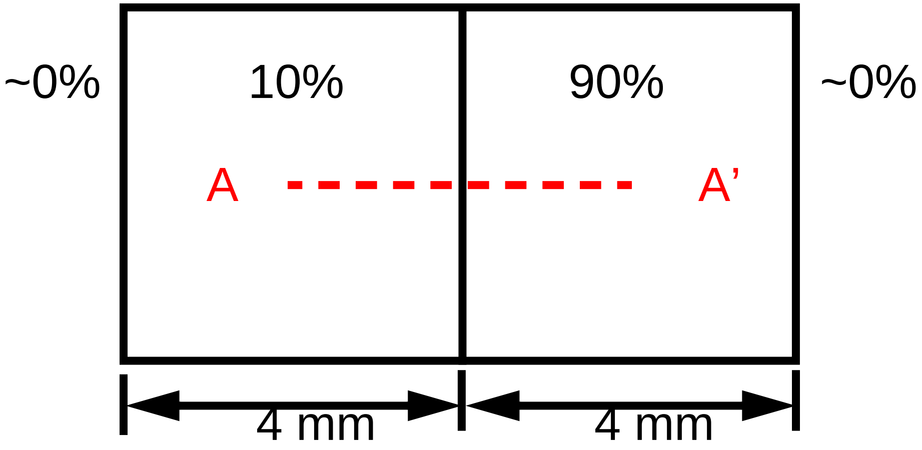


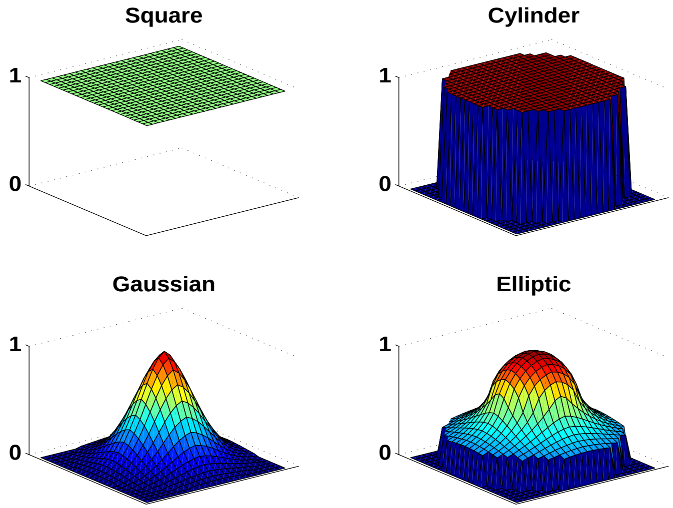
**Optimal Planarization Length**

# Outline

- Capsule Summary
- Background
  - Global Non-Planarity and Oxide Thickness Prediction
- Modeling
  - Density-Dependent Oxide CMP Model
  - Effective Density Calculation - **Square Window & Planarization Length**
  - Signal Processing Analogy - Density Step Response
- Physically-Motivated Effective Density Calculation
  - **Elliptic Window & Planarization Response Function**
- ✔ **Results:**
  - Density Step Test Structure
- Discussion and Summary

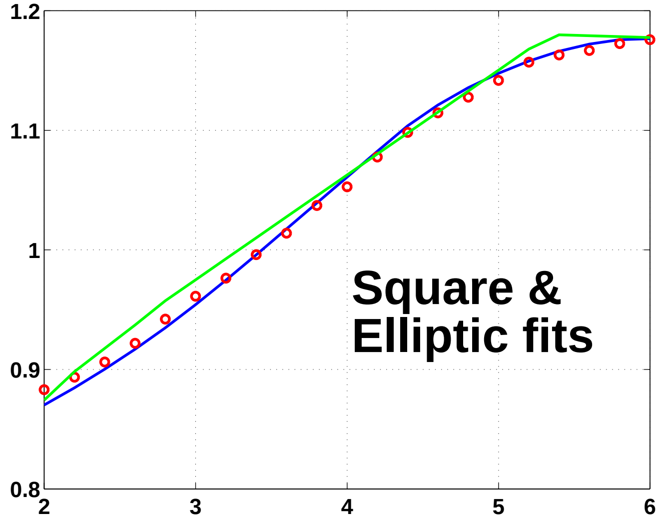
# Response Function Comparisons - Step Density



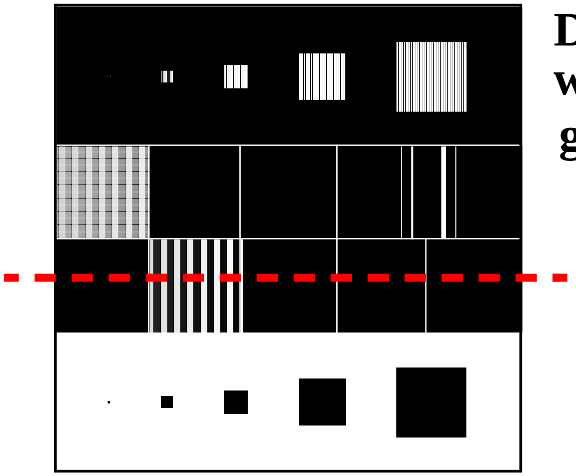


Tool/Process 1:

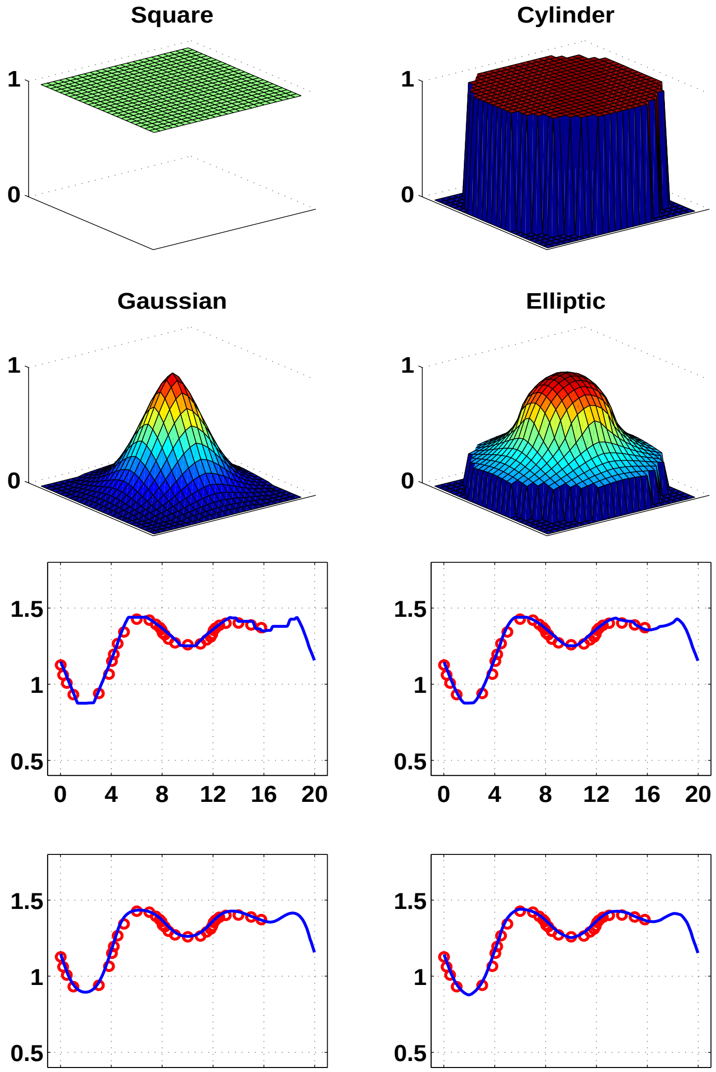
| Filter | RMS Error | Window Size |
|---|---|---|
| Square | 91Å | 5.25 mm |
| Cylindrical | 100Å | 5.85 mm |
| Gaussian | 56Å | 10.5 mm |
| **Elliptic** | **42Å** | **7.35 mm** |



# Response Function Comparisons - Test Die



Density map within small grid cells

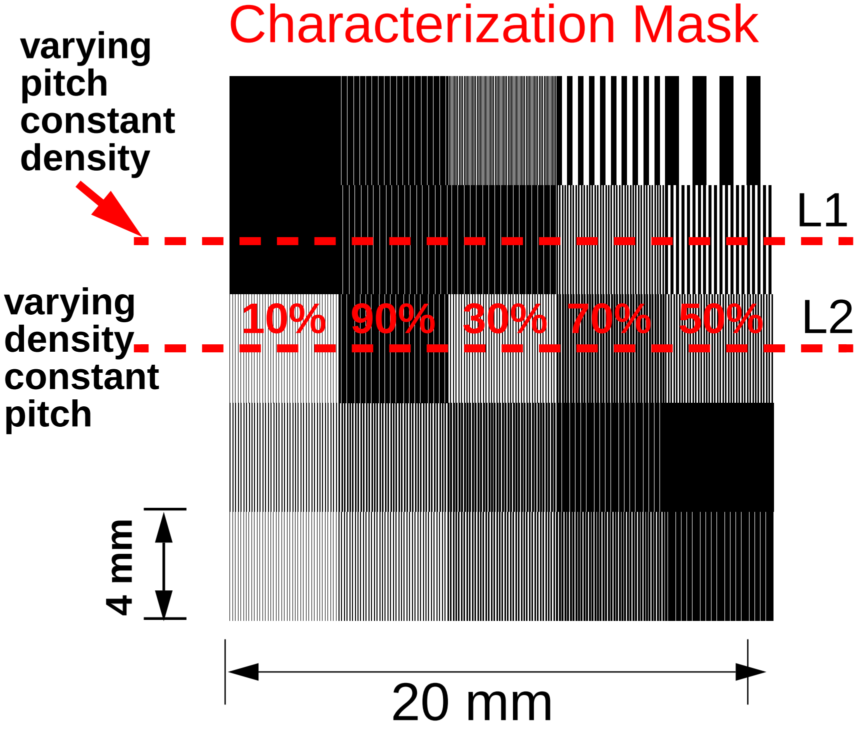


Tool/Process 2:

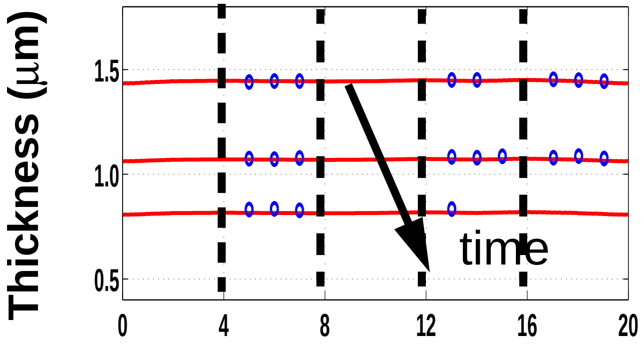
| Filter | RMS Error | Window Size |
|---|---|---|
| Square | 257 A | 2.7 mm |
| Cylindrical | 251 A | 3.3 mm |
| Gaussian | 243 A | 5.1 mm |
| **Elliptic** | **239 A** | **3.9 mm** |

# Using the Elliptic Response Function: Time Evolution

## Characterization Mask

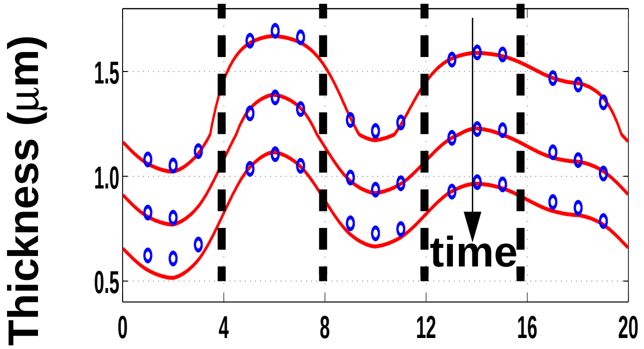


## POLISHING EVOLUTION



**L1 - Constant Density (50%)**

**No pattern effect!**



**L2 - Step Densities**

**Significant pattern effect range 5000Å at final polish**

- Can apply response function to find effective density across entire die
- Given effective density and blanket removal rate, can use time-dependent model to predict remaining oxide thickness

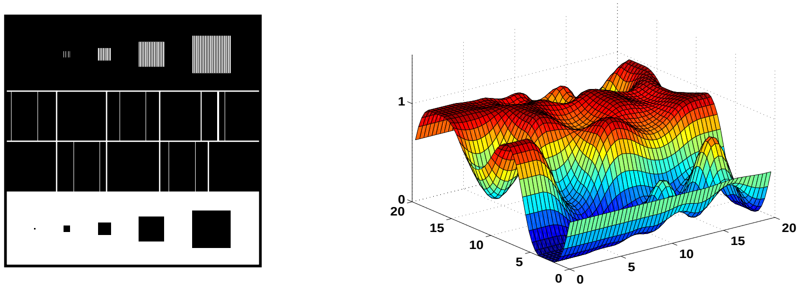
# Outline

- Capsule Summary
- Background
    - ❑ Global Non-Planarity and Oxide Thickness Prediction
- Modeling
    - ❑ Density-Dependent Oxide CMP Model
    - ❑ Effective Density Calculation - **Square Window & Planarization Length**
    - ❑ Signal Processing Analogy - Density Step Response
- Physically-Motivated Effective Density Calculation
    - ❑ **Elliptic Window & Planarization Response Function**
- Results:
    - ❑ Density Step Test Structure

✔ **Discussion and Summary**

# Planarization Length/Response vs. TIR

- **TIR = Total Indicated Range** = Max oxide thickness - Min oxide thickness
  - Measures total within-die global nonuniformity
  - Good figure of merit for a **given mask layout** and process/consumable set
  - Must know where high and low oxide thicknesses are located in die
  - Provides little information that is applicable to **other** masks
- **Planarization Length and Response Function**
  - Measures planarization capability of a given process/consumable set
  - A derived parameter based on measurements & characterization mask
  - **Powerful**: used to efficiently **predict oxide thickness for arbitrary layout:**



Effective density with elliptic filter of length 3.9 mm

  - Opportunity: relate planarization length to fundamental pad/process parameters

# Elliptic Planarization Function: Challenging Questions

- Elliptic filter found to empirically produce very good match to data

However...

- Need better physical explanation:
  - shape function related to elastic deformation
  - why deformation rather than normal stress?
  - how relate to pad hardness, pad stack, other material properties?
    - Achuthan et al. (Sandia) - large dependency on back pad
    - static vs. dynamic pad modulus?
  - how depend on or relate to other process parameters?
    - downforce, speed
    - temperature
    - slurry characteristics

# Application to Other CMP Processes

- Shallow Trench Isolation (STI)
  - Density extraction and model directly applicable to oxide polish phase in STI
  - Predict time to touch-down on nitride (Pan et al., VMIC ‘98)
  - Applicable to nitride over-polish phase in STI?
- Copper Damascene
  - Multiple pattern dependent effects:
    - Metal line dishing
    - Pattern dependent erosion -- may be amenable to density modeling, but on much shorter length scale
  - Erosion may depend on more than an effective density (Park at al., VMIC ‘98)

# Key Points and Conclusions

- Possible to predict die-level oxide thickness variation - oxide CMP model
- Proposed a new step-density test pattern to characterize planarization length
- Proposed a physically-motivated planarization response function
  - Elliptic circular window based on elastic pad deformation
- More work needed to:
  - Establish physical relationship between pad/process parameters and window shape
  - Facilitate/simplify direct extraction of window shape and planarization length

# Acknowledgments

- Dale Hetherington, Sandia National Laboratories
    - Assistance and collaboration on many aspects of oxide and STI CMP characterization and modeling methodology development
- Texas Instruments (Greg Shinn and others);
  Applied Materials (Tony Pan and others)
    - Experimental interactions on oxide and STI polishing
- This work has been supported in part by
    - DARPA under contact #DABT63-95-C-0088
    - NSF/SRC Engineering Research Center for Environmentally Benign Semiconductor Manufacturing