Die/wafer sub-micron alignment strategies for semiconductor device integration

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Outline

- *Die/wafer alignment background*

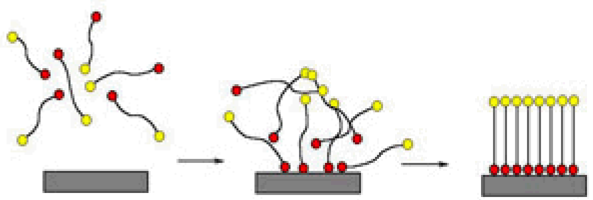
- *Patterns that maximize the tendency of surfaces to align*

- *Aligning patterned Au features*

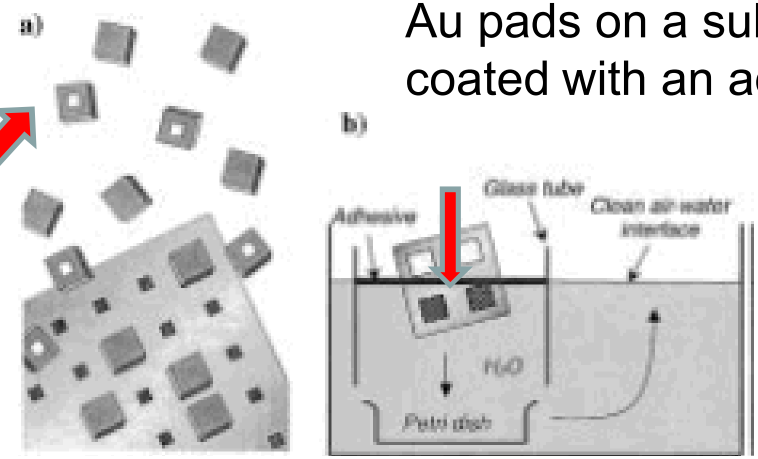
- *Au-Au bonding*

Capillary force-assisted die/wafer alignment

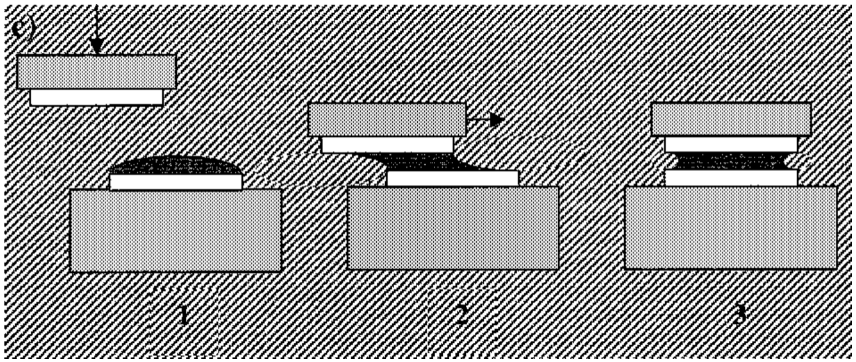
Self-assembled monolayers (SAMs) coat Au pads on the die.



Au pads on a substrate are coated with an adhesive.



Die are held in place under water by the capillary forces of the adhesive, and the adhesive is then cured.

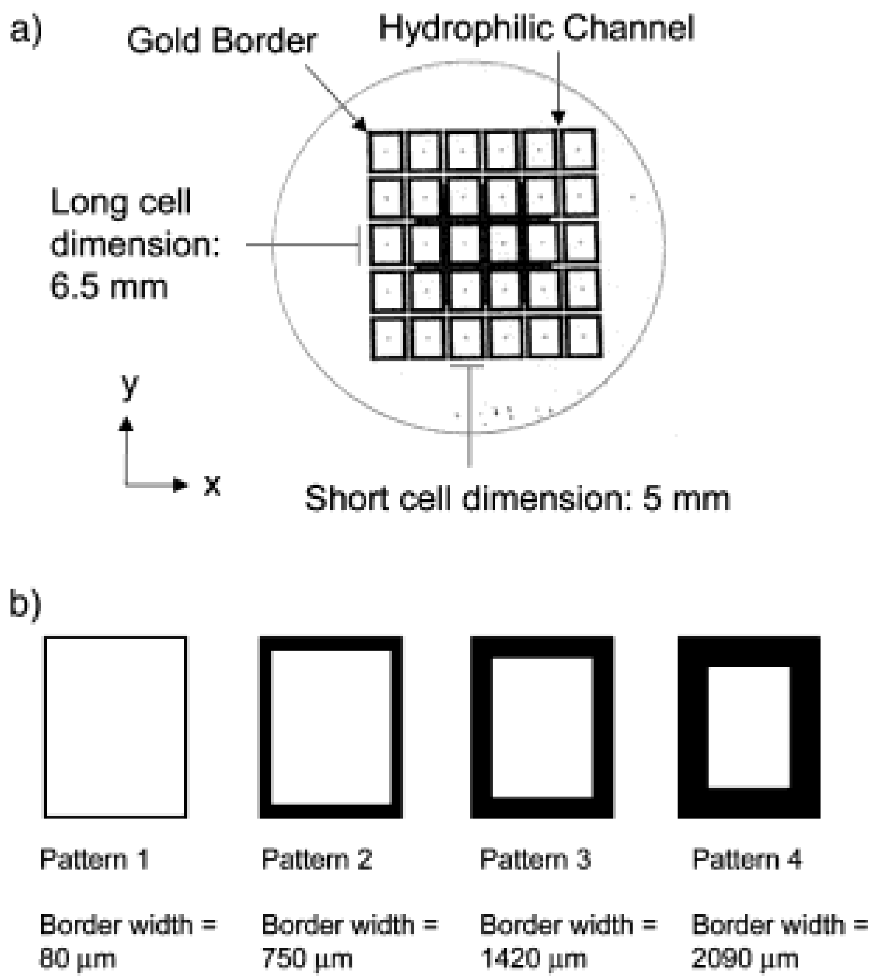


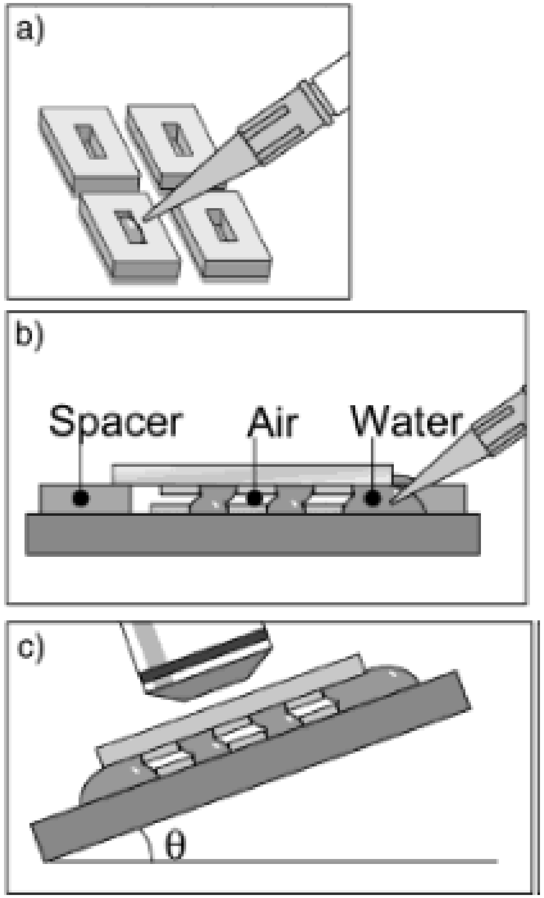
U. Srinivasan et al., J. Micromech. Sys., 10 [1], 17 (2001).

- Alignment accuracy of <0.2 μm for square pads using this technique.
- Use of adhesives and water baths limits the applicability of the technique.

Adhesive-free capillary force-assisted wafer alignment

- Water droplets have been used to align 2” to 3” wafers.



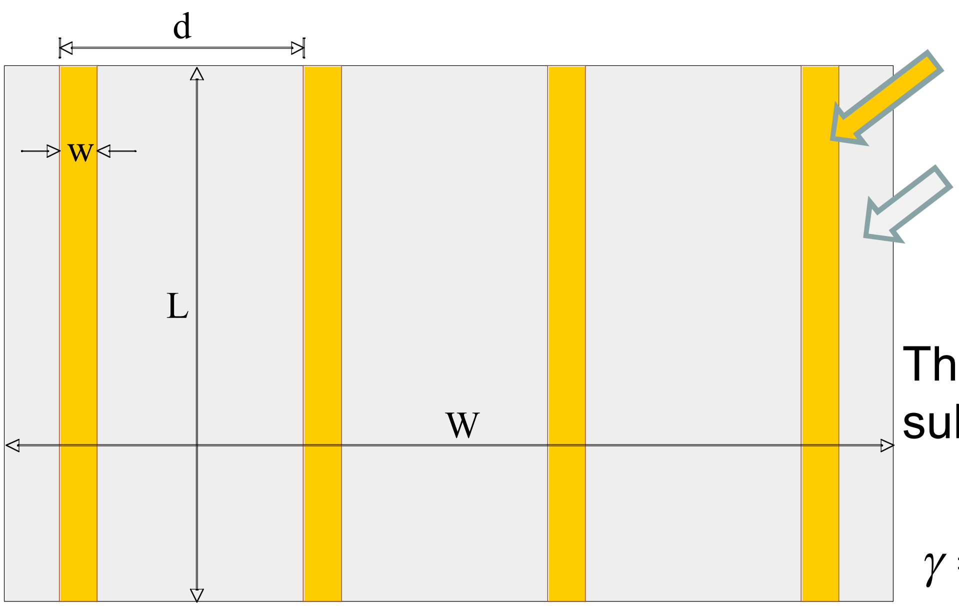


BR Martin et al., Adv. Funct. Mater., 11 [5], 381 (2001).

- Submicron alignment is possible with this method, but the trapped H_2O is problematic.

We are exploring self-aligning patterns

•A simple case is two surfaces patterned with lines, with only lateral misalignment.



The interfacial energy per unit area of substrate for $0 \leq x \leq w$:

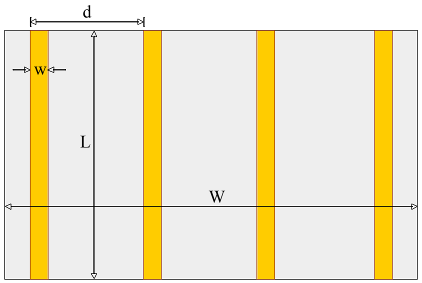
$$\gamma = \frac{w-x}{d}\gamma_{AA} + \frac{2x}{d}\gamma_{AB} + \frac{d-w-x}{d}\gamma_{BB}$$

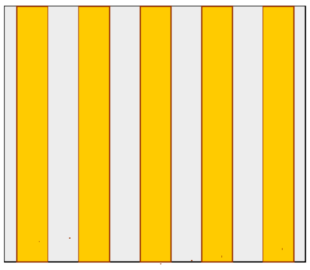
where $w = \alpha d$ and $\Delta\gamma = 2\gamma_{AB} - \gamma_{AA} - \gamma_{BB}$

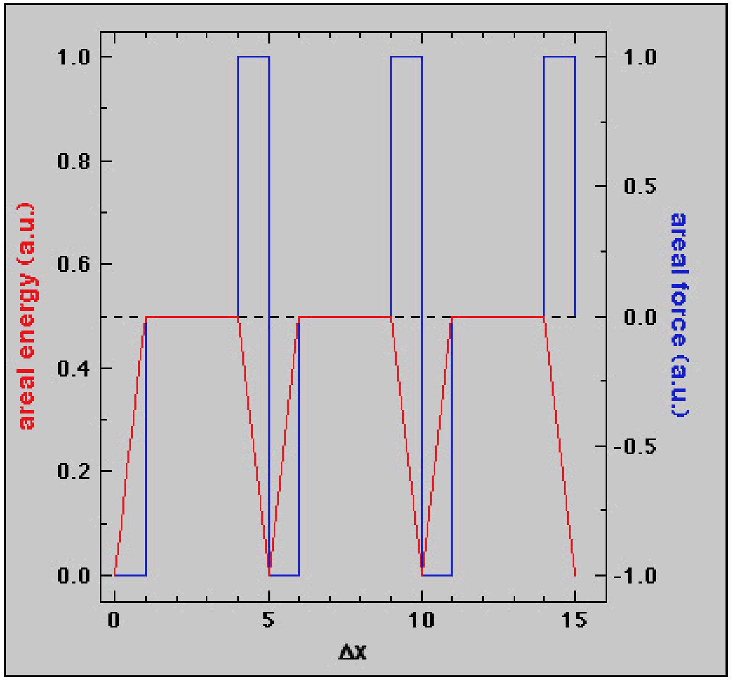
The lateral force per unit area: $f = -\frac{d\gamma}{dx} = -\Delta\gamma / d$

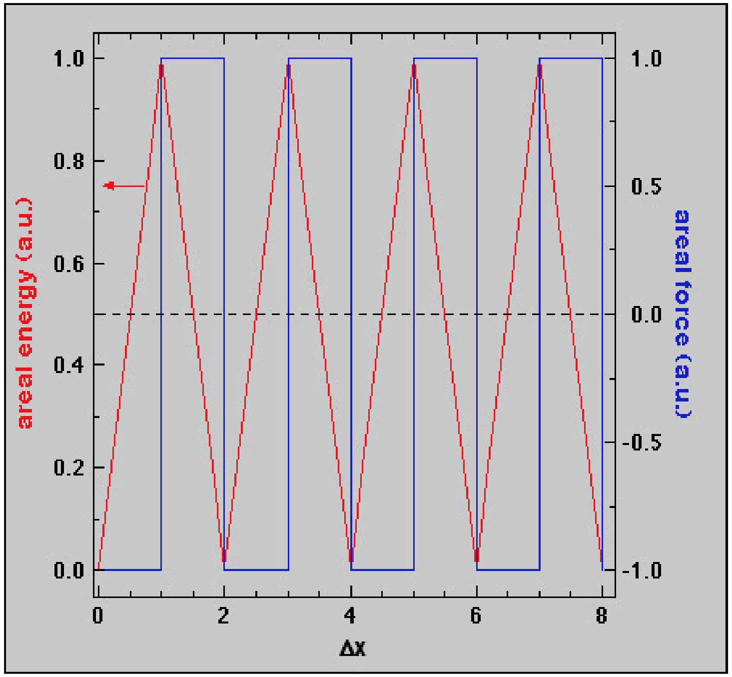
• Registration force is inversely proportional to the line spacing.
• Areal force is independent of the dimensions of the substrate.
• When w<x<d-w, the registration force is zero.

Patterns can be designed to tolerate initial misalignment







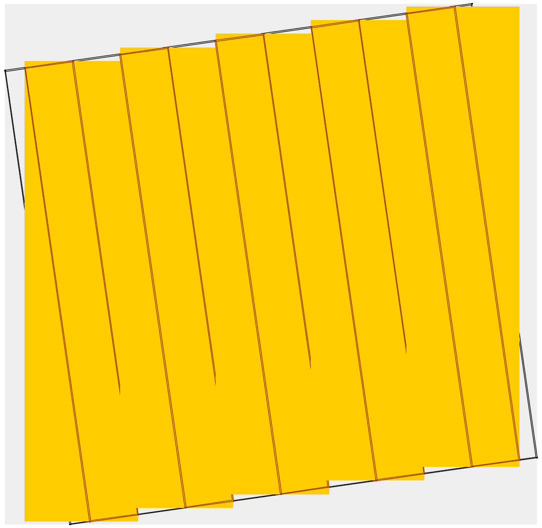


- When there is no overlap between material A lines, there are gaps of zero force.

- When the line width is half the periodicity, there is always a positive or negative force,

Angular misalignment can produce an aligning torque

- We consider a series of lines that are misregistered by an angle θ.
- Each line overlaps with the underlying lines throughout its entire length.



The surface energy:

$$\Gamma = \frac{W}{d}\frac{L^2}{2}\tan\theta\gamma_{AB} + \frac{W}{d}(wL - \frac{L^2}{4}\tan\theta)\gamma_{AA} + \frac{W}{d}\left((d-w)L - \frac{L^2}{4}\tan\theta\right)\gamma_{BB}$$

$$= \frac{W}{d}\left[wL\gamma_{AA} + (d-w)L\gamma_{BB} + \frac{L^2}{4}\Delta\gamma\tan\theta\right].$$

Differentiating w.r.t. θ gives the torque on the upper substrate:

$$\mathrm{T} = -\frac{d\Gamma}{d\theta} \approx -A\frac{L}{4d}\Delta\gamma$$

where *A* is the substrate area

- Torque is similar to the lateral force in that it increases with decreasing feature size, *d*, and can be substantial.
- T also scales with the line length.

Longitudinal force on an array of lines

- y denotes the displacement parallel to the lines of the top substrate relative to the bottom substrate, whose size is LxW.

The total surface energy:

$$\Gamma = (L-y)W\left[\frac{w}{d}\gamma_{AA} + \frac{d-w}{d}\gamma_{BB}\right] + 2yW\left[\frac{w}{d}\gamma_{A} + \frac{d-w}{d}\gamma_{B}\right]$$

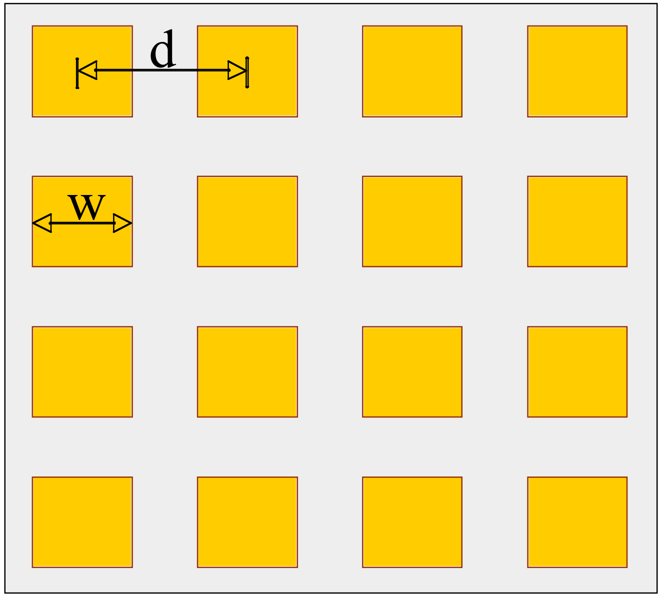
Differentiating w.r.t. y gives the total force:

$$F = W\left[\frac{w}{d}(2\gamma_A - \gamma_{AA}) + \frac{d-w}{d}(2\gamma_B - \gamma_{BB})\right]$$

- Total longitudinal force depends only on the substrate width
- This force scales as W, whereas static friction scales as LxW, so is negligible.

Lateral and longitudinal forces require pad arrays

- A square lattice of square pads can be viewed as an array of dashed lines.



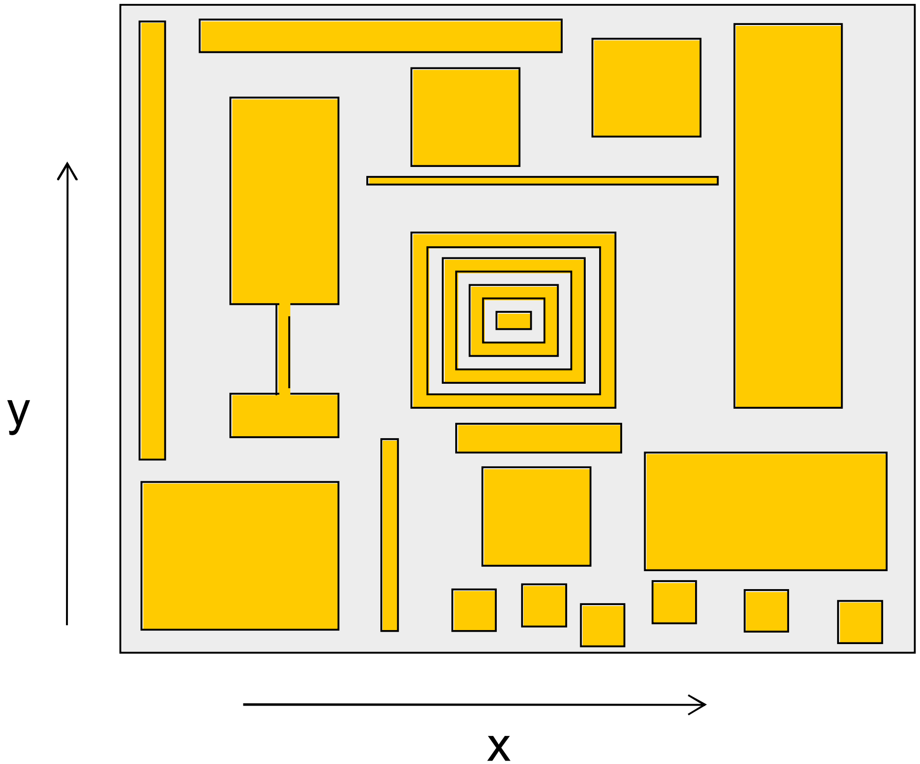
The lateral and longitudinal areal force:

$$f = \frac{w}{d^2}\Delta\gamma$$

- When w=1/2d, this areal force is half that obtained with lines.

Forces on an assembly of rectilinear pads

• The pad array result can be generalized to any assembly of rectilinear objects with their sides mutually aligned.

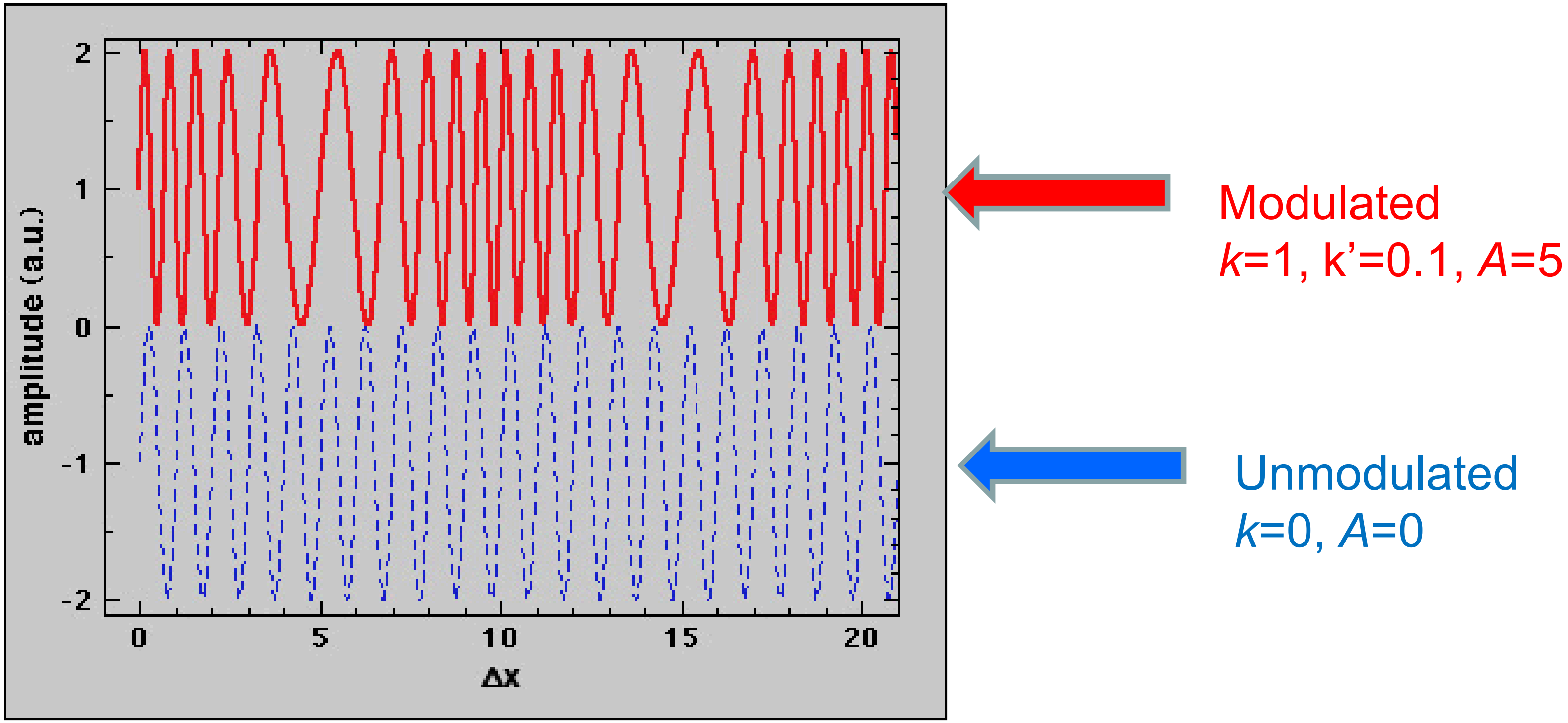


•Such pad arrays point the way to extremely precise alignment: A succession of features of ever-decreasing size could lead to highly precise alignment given a rough initial placement.

More complex alignment patterns

- Line arrays with a sinusoidal modulation in their spacing.

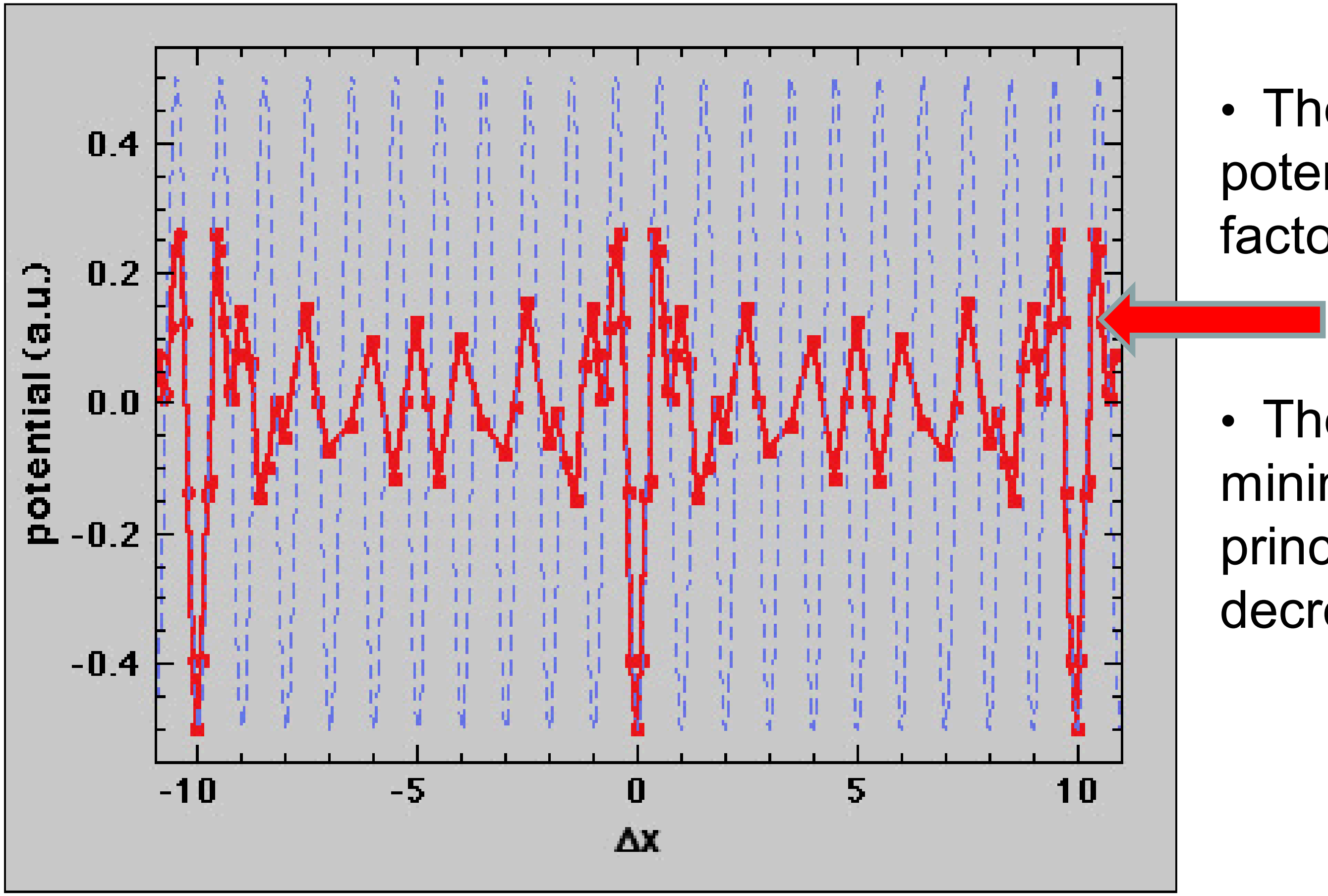
$$C(x) = \sin(2\pi k x + \phi(x)) \qquad \phi(x) = A\sin(2\pi k' x)$$



The' potential surface' is then defined by:

$$U(\Delta x) = -\lim_{X\to\infty}\frac{1}{X}\int_0^X C(x)C(x+\Delta x)\,dx$$

Modulated patterns need less precise initial alignment

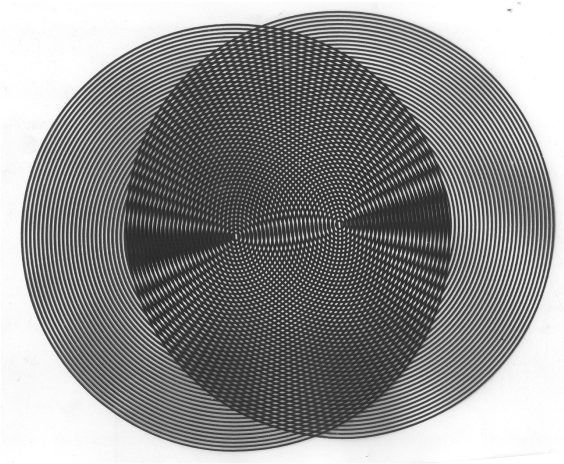


- The periodicity of the potential increases by a factor of k/k'=10.

- The amplitude of the minima in between the principal minima decreases.

The optimal registration pattern?

• Moire pattern that occurs when two patterns of regularly-spaced rings overlaps.



• Such a pattern has a *single, strong energy minimum* and an associated radial force.

• A large torque would occur if two of these patterns were placed at opposing corners of a die.

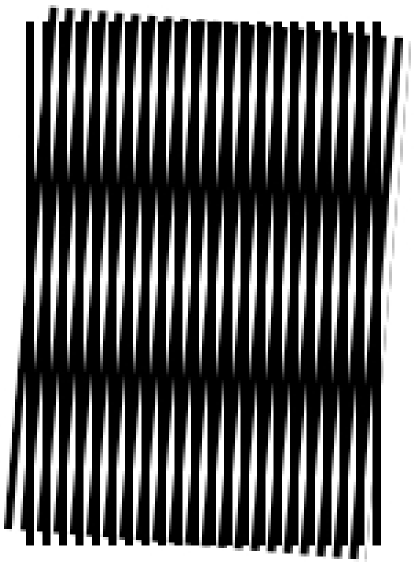
• A single spiral pattern would generate a radial force and a torque, both with a single minimum.

Experimental results

- Registration of *SAM-coated and uncoated Au line arrays*
  - *Au-Au bonding*

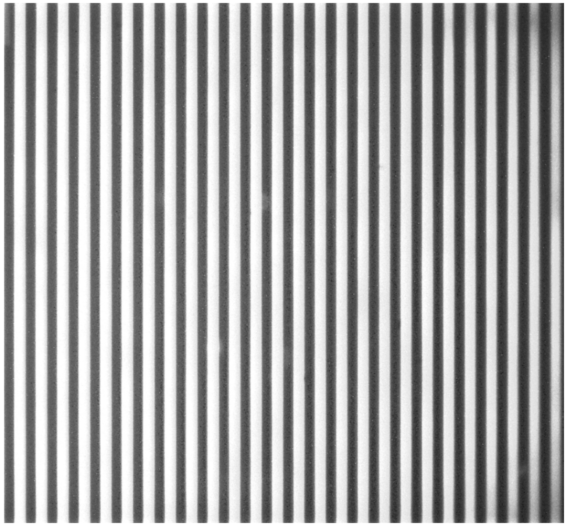
Experimental validation of pattern registration

- 2 cm square die with 25 μm-wide Au lines separated by 25 μm.
- The Au surfaces were left bare or coated with dodecanethiol.



- Misoriented lines produce a Moire pattern.

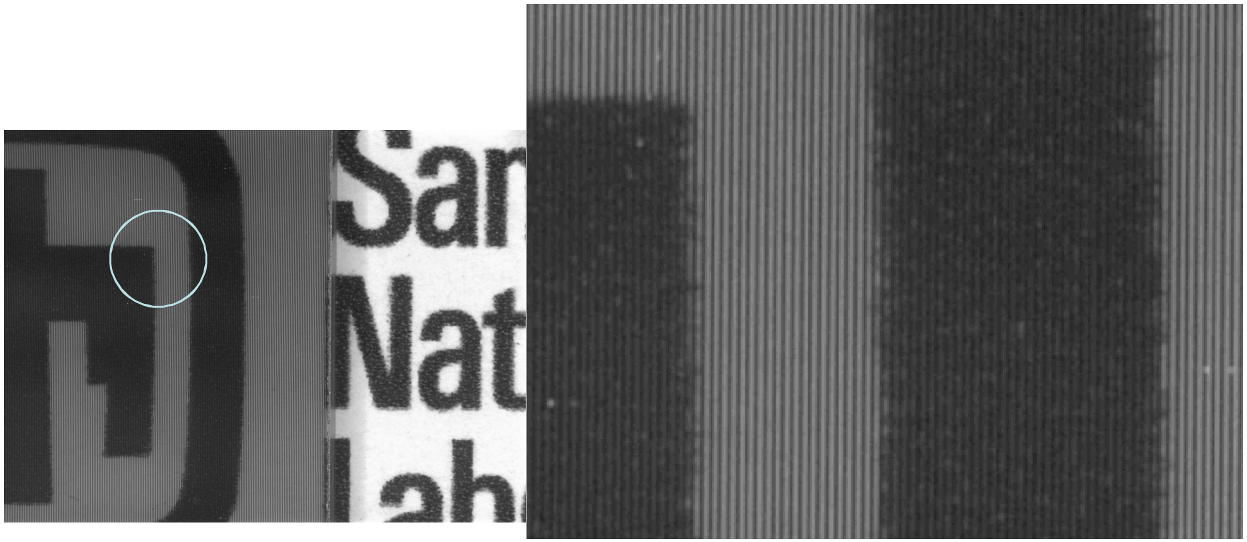
Manually prodding the top die brought the lines into alignment.



- Surface interaction between the Au lines enable essentially perfect alignment manually.

What if the patterns are SAM coated?

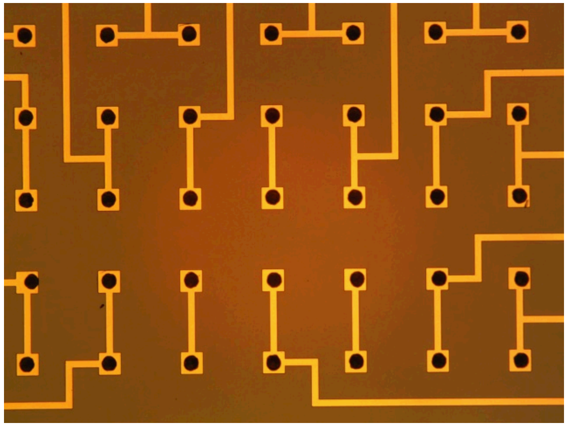
- Imaging through aligned die that have dodecanethiol-coated Au lines.



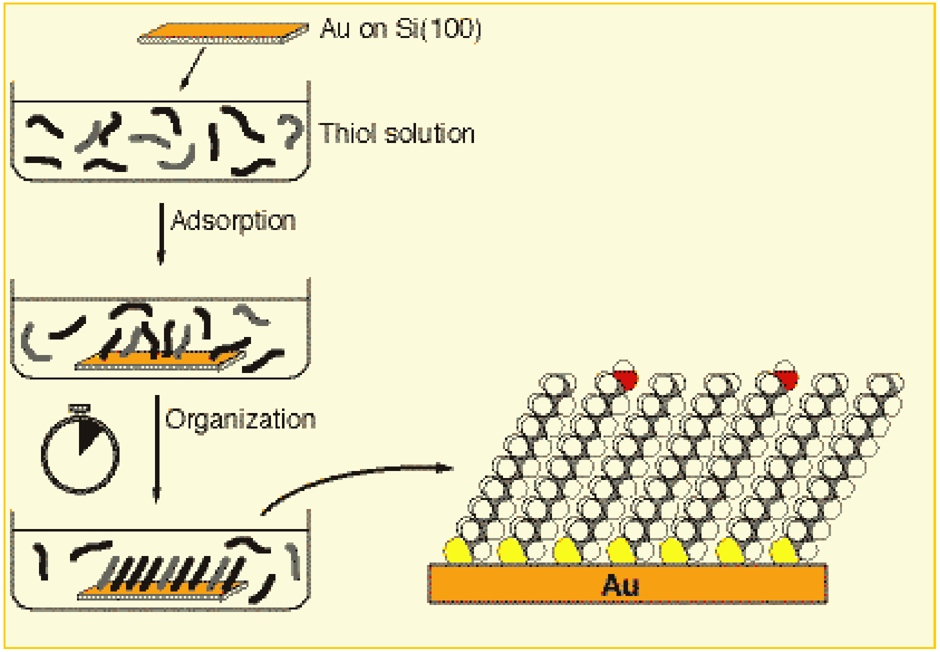
- SAM-coated die typically align in less than half the time as for uncoated die.
- SAM coatings may improve the bondability of the Au patterns.

Bonding SAM-coated Au stud bumps

- 8 x 8 array of 25 μm-tall stud bumps.



- Three surface treatments:
  - Argon plasma (1 min., 100W)
  - 5:1:1 DI-H_2O:H_2SO_4:H_2O_2 5 min.
  - SAM coating (1mM dodecanethiol in ethanol for 24 h).

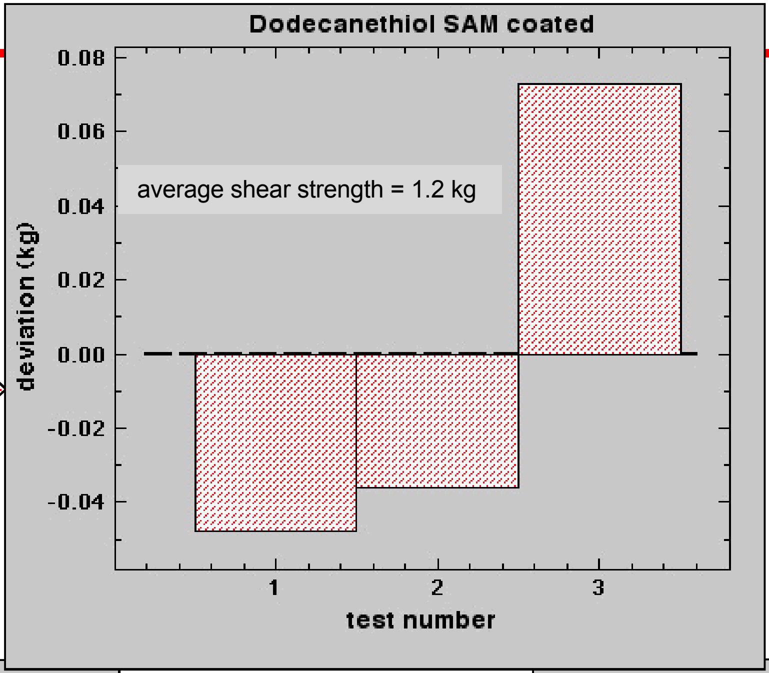


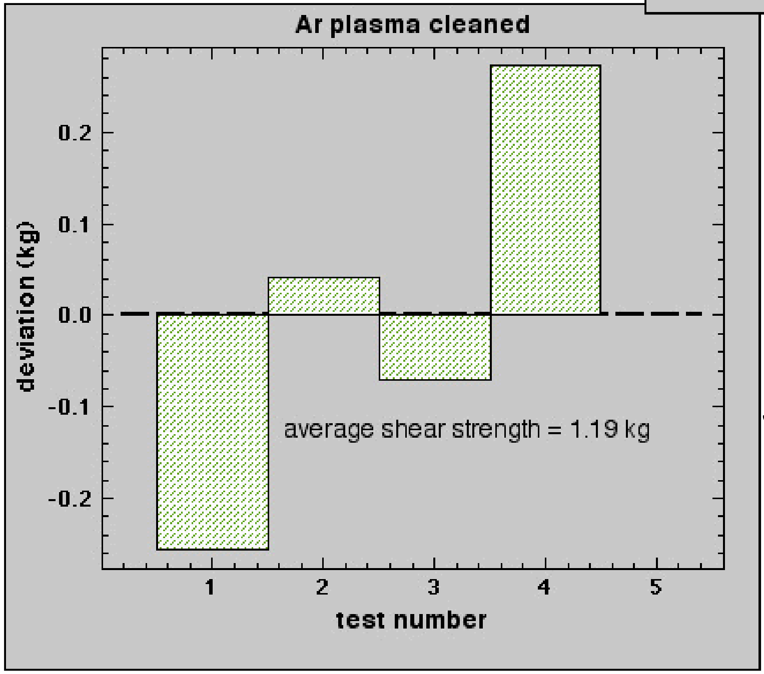
- Bonding was done at 150-155°C for 40-45 seconds under 20N.

Shear strengths as a function of surface treatment

•SAM-coated bumps:

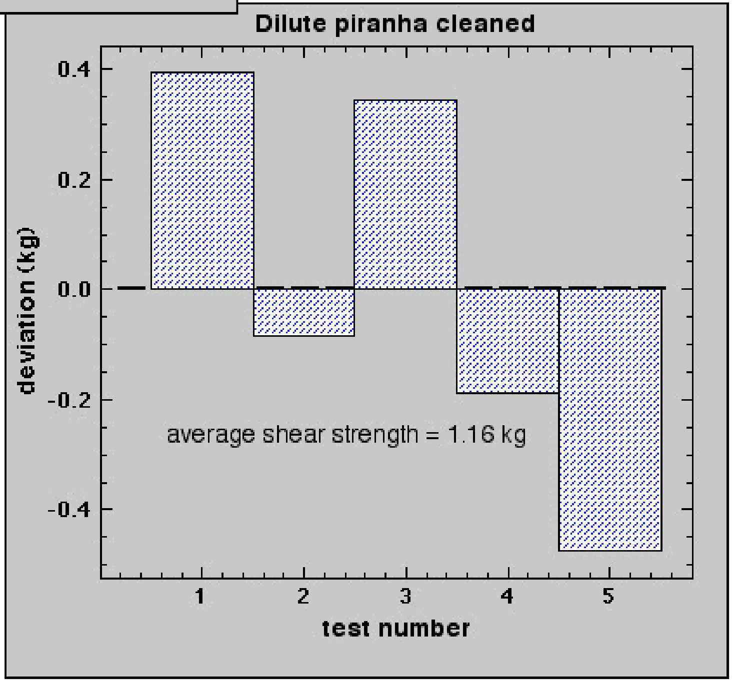
Shear strength independent of time till bonding; small deviation from the average.





•Uncoated bumps:

Shear strength depends on time till bonding; greater deviation from the average.



Summary

•We have demonstrated the feasibility of using interactions between patterned surfaces to vastly increase the alignment accuracy.

• Future work will utilize patterns that reduce the need for accurate initial placement, and that do not lead to misregistration, as can occur in patterns with translational symmetry.

• Alkanethiol SAM coatings on the Au surfaces enables alignment in less time than for the uncoated Au.

• The SAM-coated Au features can be bonded at 150-155^{o}C.