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Use of Harsh Wafer Probing to Evaluate various Bond Pad Structures

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Outline

- The need for more robust bond pads
- Harsh probing experiments on traditional bond pads
- Harsh probing on experimental pad structures
- Discussion of results, theory
- Crack prevention in wafer probe by pad design
- Summary
- Future work
- Acknowledgements

The need for more robust bond pads

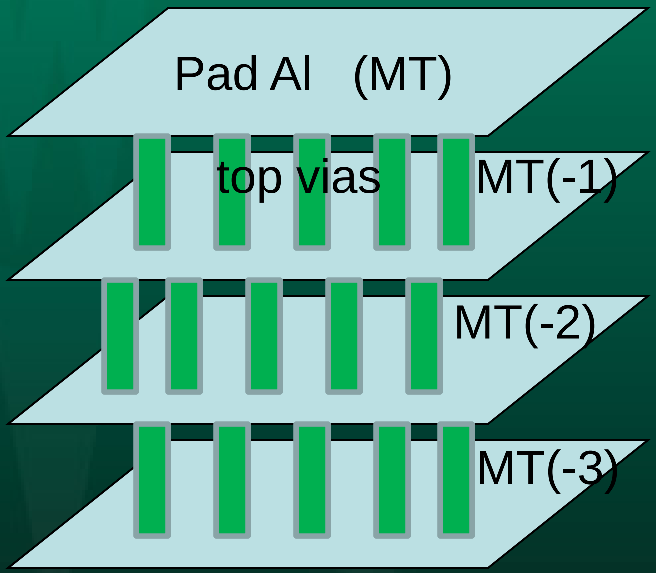
Product needs:

- **bond-over-active-circuitry (BOAC)**
  - maximum pad design flexibility for small die size, "pad anywhere"
  - 2 – 7 levels of metal
  - interconnect circuitry in all levels below the pad metal, (& ESD protection)
  - metal deformation and pad cracks are *not* acceptable
  - thick top metal is generally *not* an option
- **Cu wirebond to replace Au wirebond**
  - increased stress to pad structure
- **low force wafer probe**
  - up to 6 probe touchdowns (NVM, high and low temp. testing, …)
- **higher reliability**
  - traditional pad structure cracks easily in both probe and bond
- ***… while decreasing cost***

➢ ***Need "robust" bond pads, new bond pad design rules !***

Traditional bond pads in tests

A 4-level metal pad structure within the "pad window" is illustrated in concept:



Al metallization: TiN / Al(0.5%Cu) / TiN, W vias, SiO_2 dielectric

- sheets of metallization at all levels
- via arrays connecting the plates
- SiO_2 dielectric surrounding

(Periphery of pad structure, passivation, Si devices, etc. are not shown)

"Cratering Test"

- **Cratering Test (removal of pad Al, then visual inspect)**
  - Etch in KOH or "PAN etch" (phosphoric-acetic-nitric) solution to remove Al from pad, but purposely leave some of the TiN barrier film in place
  - visually observe top SiO_2 cracking
  - visually observe other damage: "lifting barrier", other loss of adhesion, craters
  - optical "ripple effect"
    - deformation in underlying metal interconnect (verify by FIB or XSEM)
  - not all damage can be seen by cratering test
    - *cannot detect weakened locations*
    - *may not see cracks in SiO_2 if the TiN barrier is not broken*
    - *cannot detect partially cracked locations on the bottom of the SiO_2*

Pad Damage Concerns

Probe damage on bond pads can lead to:

- **poor wirebond**
  - large area, depth of gouge
  - cracks that weaken the bond
  - film loss of adhesion
- **long term reliability concerns**
  - (the above)
  - (for Au wirebond) non-uniform voiding or resistance issues relating to intermetallic compound difference at probe location
  - cracks cause leakage or shorts in BOAC
  - cracks may widen or propagate during assembly, and in use

Cratering test example photos

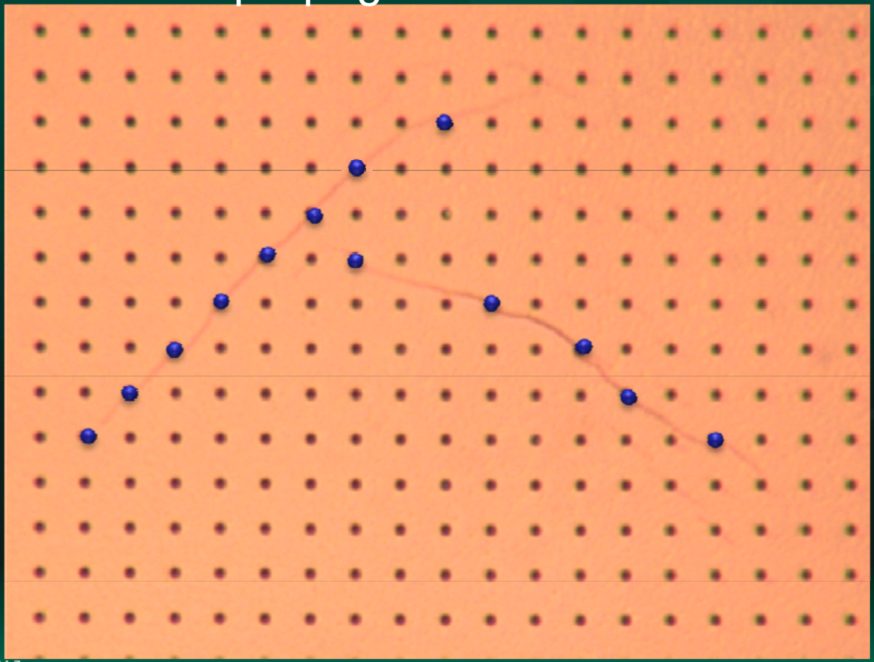
- **Cratering test removes the pad Al and the probe mark**
- **Usually etch only the Al to leave TiN barrier**
  - easier to see the cracks (highlighted in red below)
- **Can also overetch the TiN to reveal etch damage in the underlying metal layer**

	Pad 1	Pad 2	Pad 3	Pad 4	Pad 5	Pad 6
Probe Mark						
Normal Etched						
Over Etched						

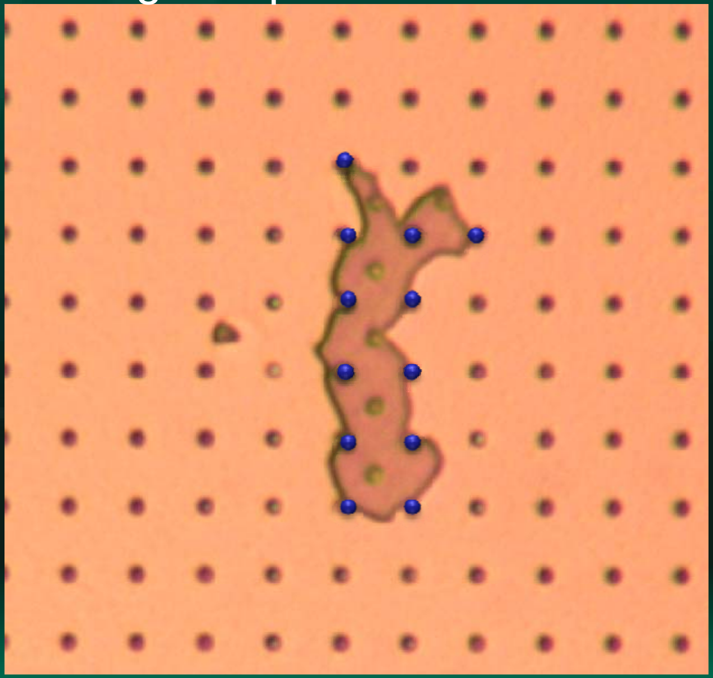
Damage relating to top vias

- **top vias participate in SiO_2 cracking, giving traditional pads with top vias the worst record for cracking**
- **lifting TiN, SiO_2 divots, and craters are much more likely with top vias**

cracks propagate from via to via



an example of "lifting barrier", relating to top vias



Proposed experiments

***Assume:* if a pad structure can withstand harsh probing without cracking, it will be more robust in wirebond as well …**

***Plan:* Experiment with traditional pads and choose a "harsh" probing condition, then probe "harsh" on pad design variations**

- *Cantilever probe cards*
- *WRe probe tips, 0.8 mil diameter, ~105 degree bend angle*
- *TSK UF-200 prober*
- *sample: at least 40 pads per die, at least 3 die per condition*

factor	abrev	levels
chuck overdrive	OD	**1, 2, 3, 4 mils**
number of touchdowns	TD	**1, 2, 6**
probe tip length	TL	**17.5, 28.5 mils**
top metal Al thick	MT	0.55, **0.8**, 1, 1.5, 3 um
top vias	VT	**dense**, sparse, none

Traditional bond pads after harsh probing

1. *Chuck overdrive is the strongest factor for cracking*
2. *Probe touchdowns is a strong factor when high overdrive*
3. *Short probe tips are worse for cracking*

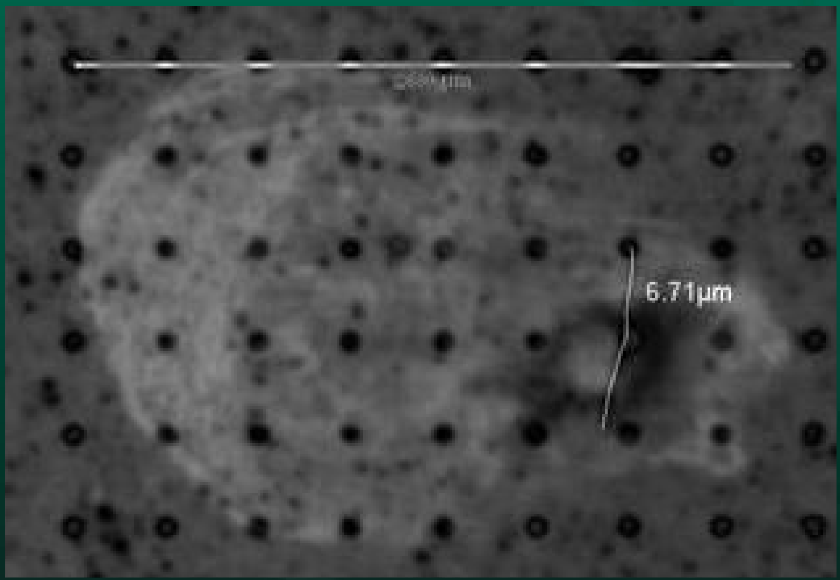
- *(Thick top metal >1um reduces cracking)*

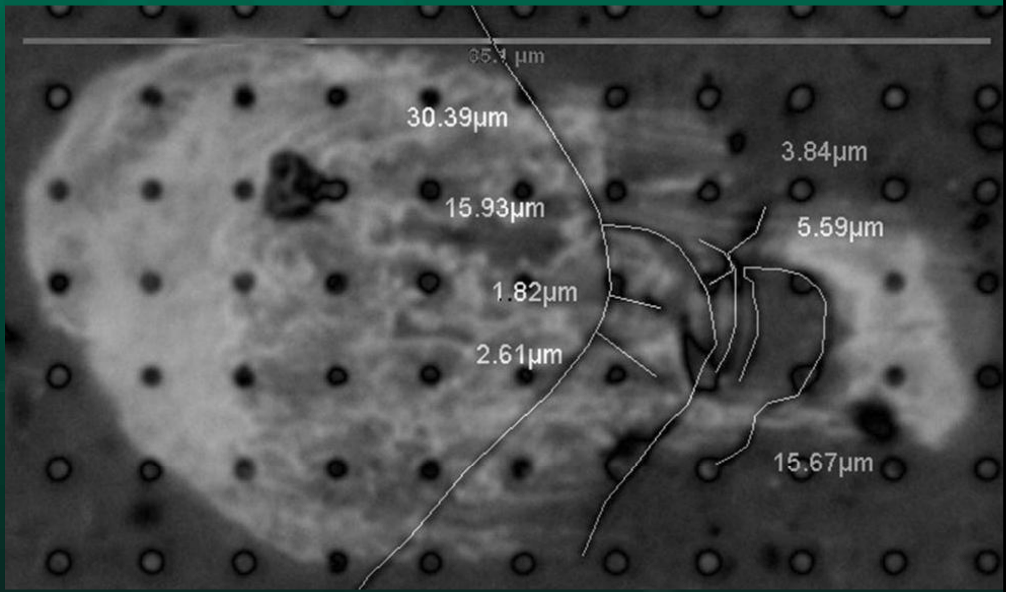
Traditional pads probed at 4mils OD, 6 TDs

data combined from many experiments, 4 different technologies

traditional pad design	% pads cracked: 6 TD, 4mil OD	Ripple effect	other damage
0.55um MT, dense VT	95 - 100 %	strong	some barrier lifting
0.8um MT, dense VT	90 - 100 %	strong	some barrier lifting
0.55um MT, no VT	60 – 90 %	strong	
0.8um MT, no VT	40 – 90 %	strong	
1.0um MT, no VT	20 - 50 %	strong	
1.5um MT, no VT	15 - 25%	reduced	
3.0um MT, no VT	0	barely visible	

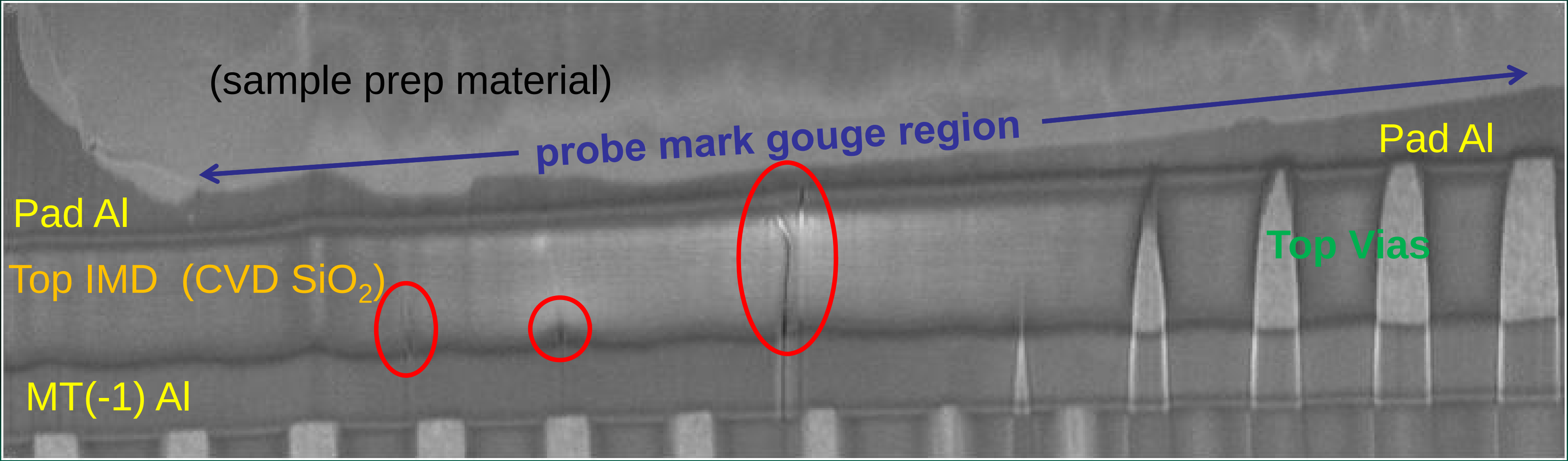
Examples of pad crack photos overlaid with the probe marks





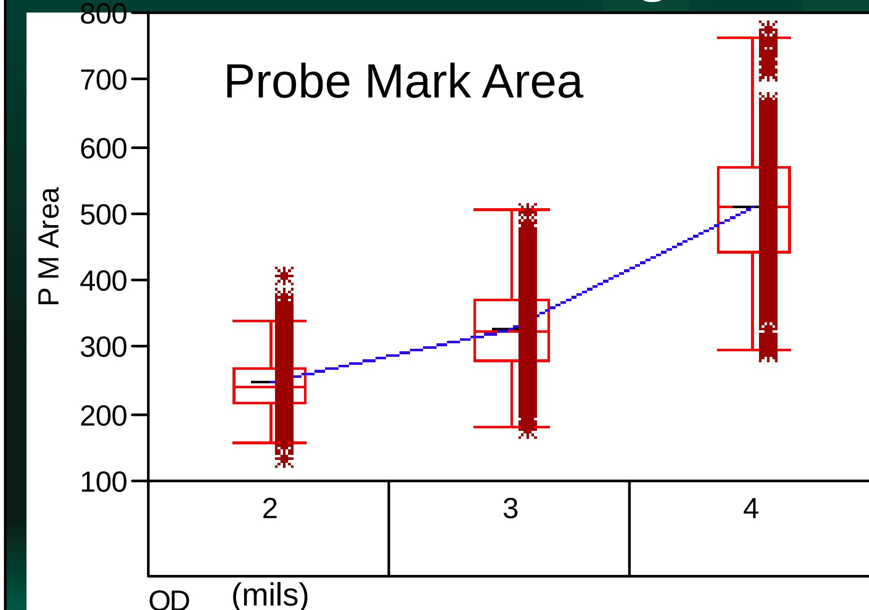
Crack initiation from probing

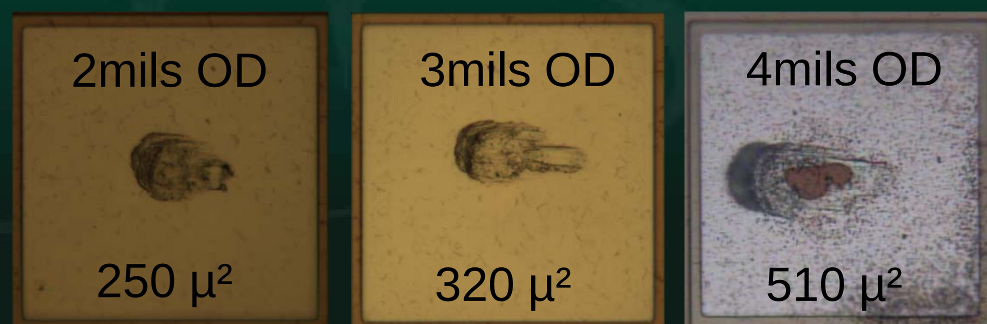
- **This FIB cross section of a probe mark on a traditional pad structure shows 4 cracks in the top dielectric**
  - 3 cracks initiate in the bottom of the dielectric
  - cracks are located near the deepest part of the probe mark
  - only one is easily visible in a cratering test: cracked TiN
  - cracks will become worse (propagate, widen) during wirebond



Chuck overdrive

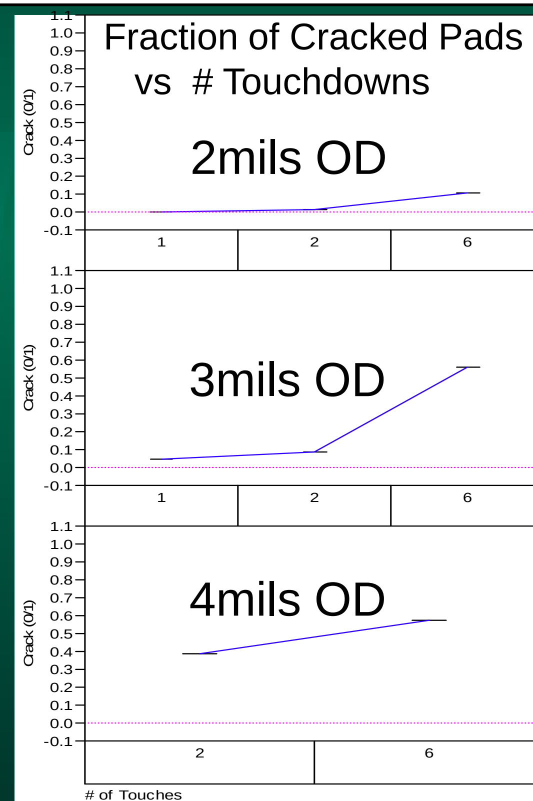
- **Chuck overdrive increase is the largest factor in causing cracks for traditional bond pads**
  - probe mark size increases
  - probe mark depth increases
  - % of pads cracked increases
  - number and length of cracks increases



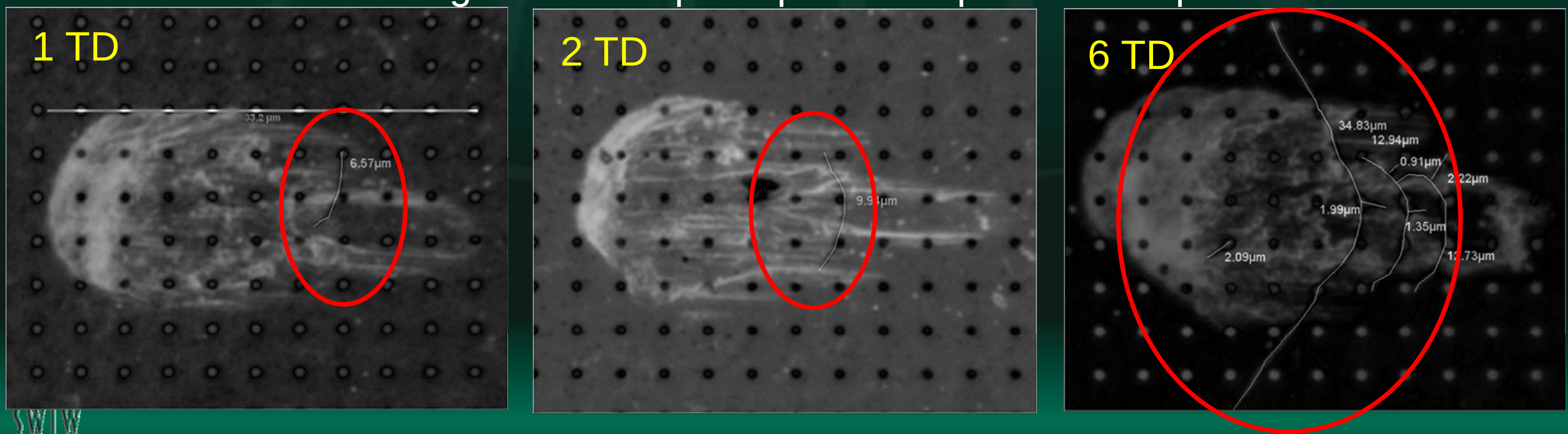


Number of touchdowns

- **Probe touchdowns is not a large factor in cracking until the overdrive is high on traditional pads**
- **crack length and number of cracks increase with more touchdowns**

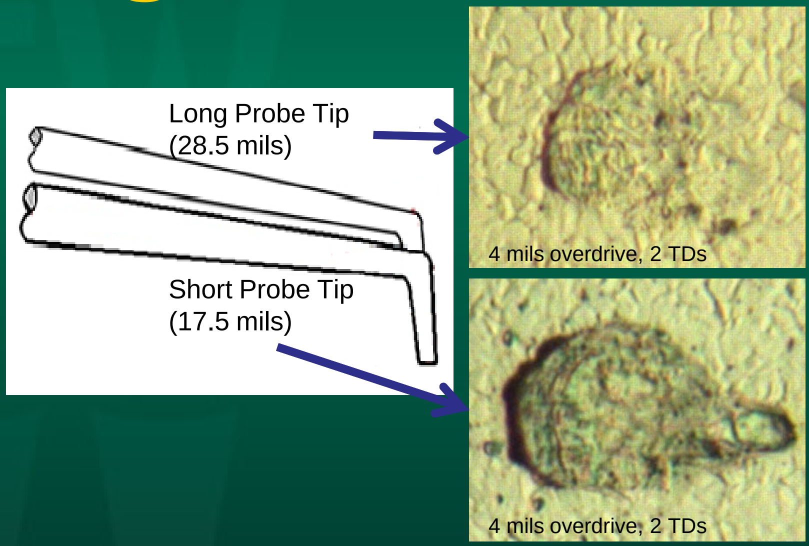


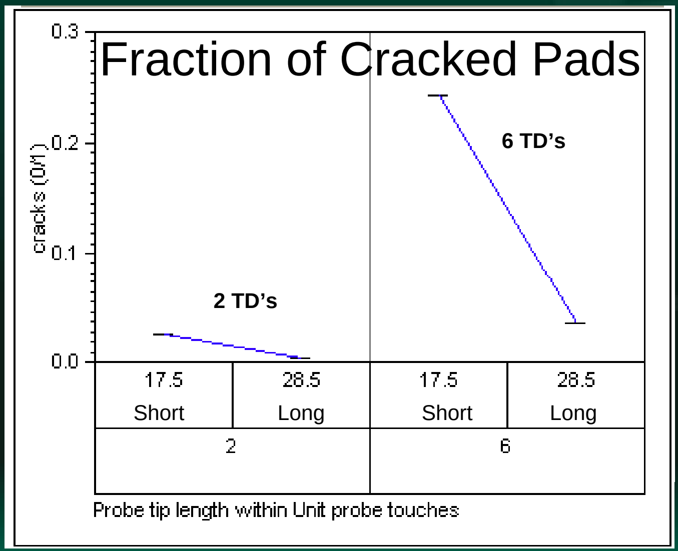
below: cracks in cratering test are superimposed on probe mark photos

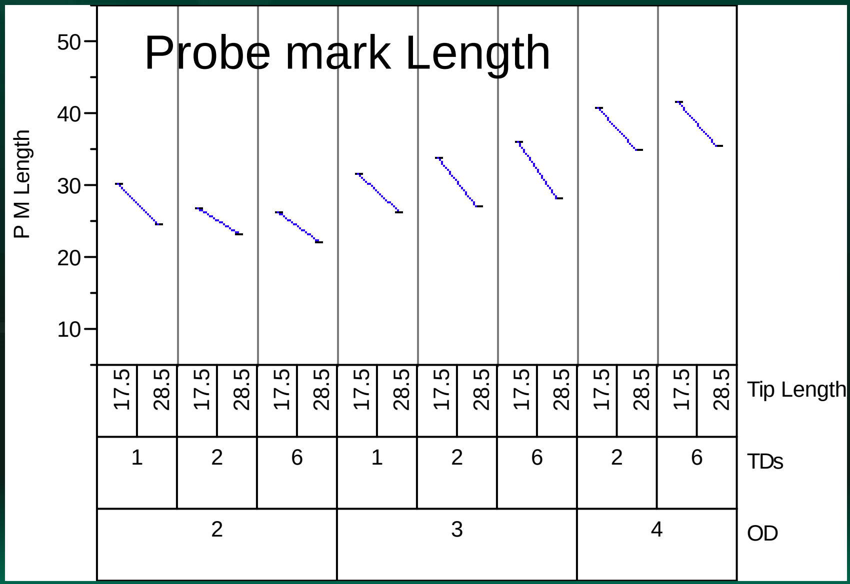


Probe tip length

- shorter tip length causes more cracks, most apparent with high touchdowns on traditional pads
- shorter tip length causes longer probe mark

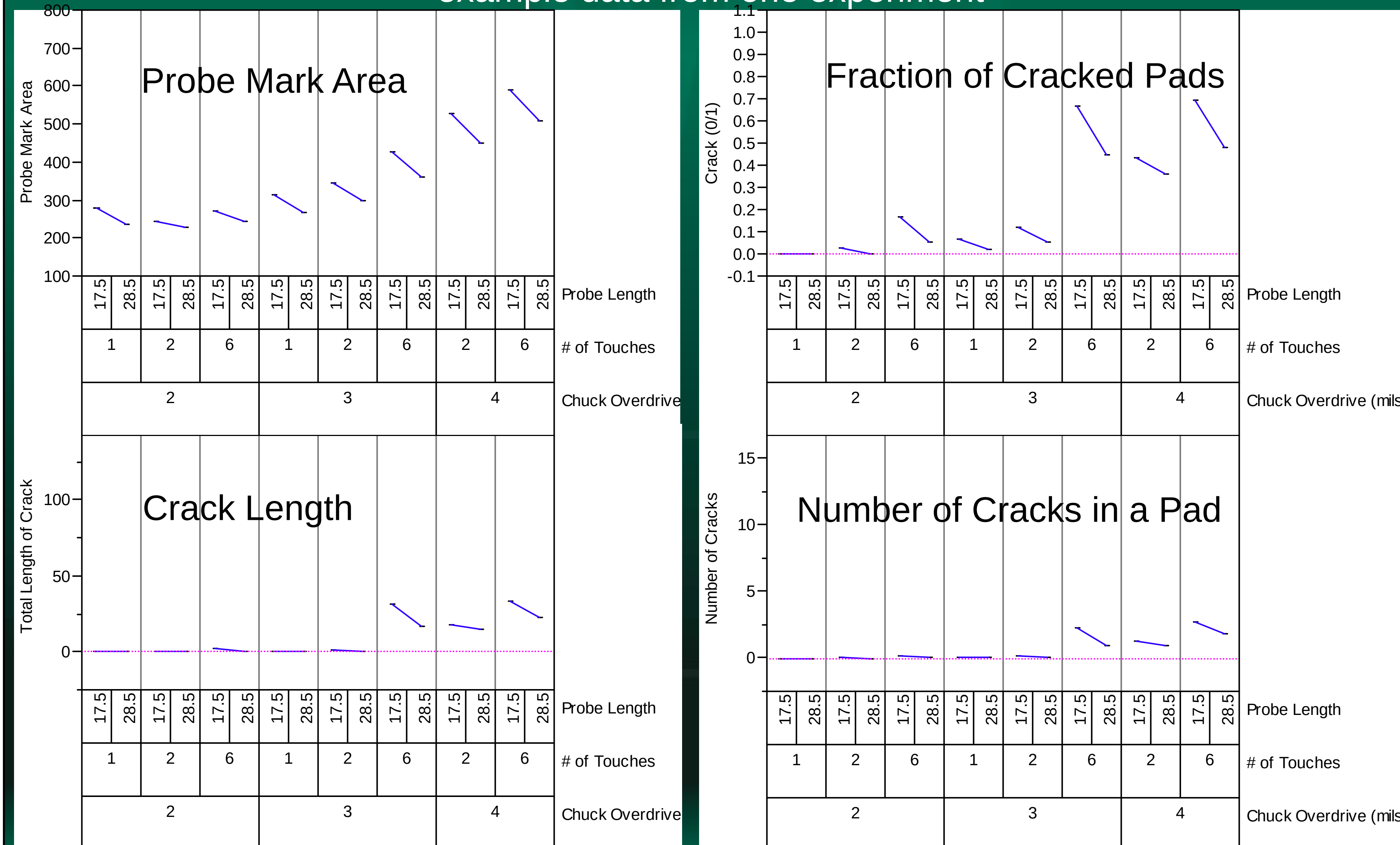






main factors interactions for traditional pads

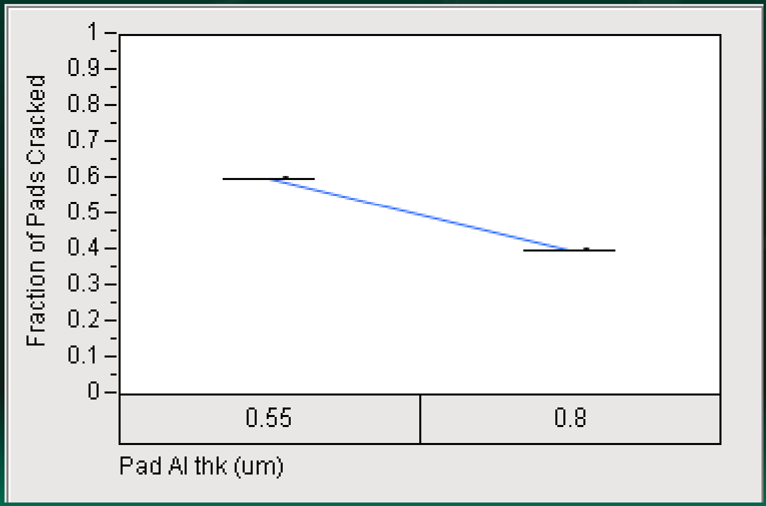
example data from one experiment

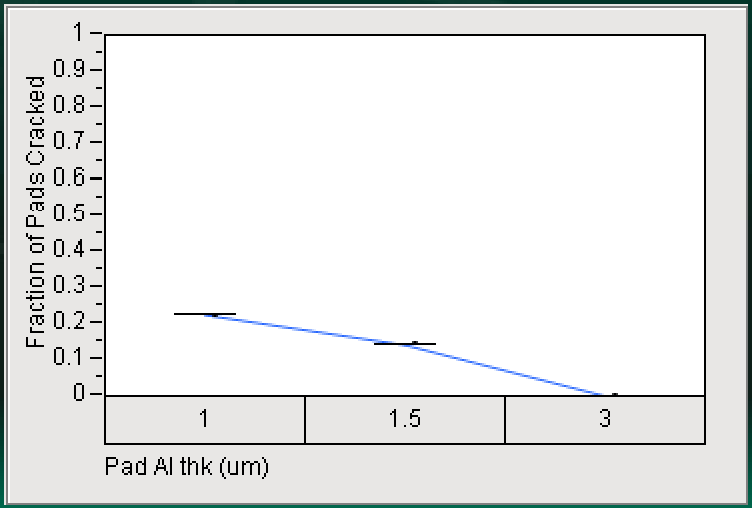


Pad Al thickness

- **Cracking reduces with increasing pad Al thickness**
  - harsh probing conditions reveal this dramatic trend
  - pad Al thickness of 3um prevents cracks from harsh probe

Example experiment data below is from two different technologies;
No top vias, 6 Touchdowns at 4mils Overdrive

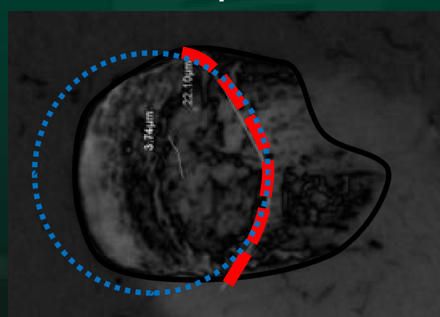




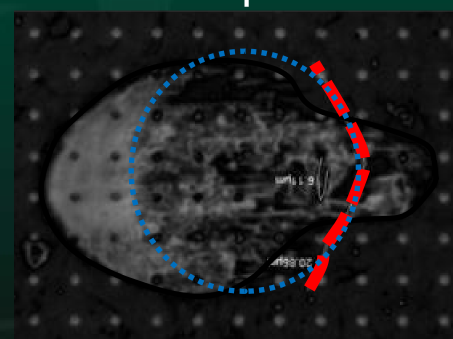
Crack characteristics

- **Cracks (red) tend to form with a radius the same as the probe tip (blue)**

Probe Mark from Long Probe Tip, no top vias



Probe Mark from Short Probe Tip, with top vias



Direction of probe scrub

Harsh bonding experiment plan: pad structure variations

factor	levels					
Pad Al	**.55um**	**.8um**	1.0um	1.5um	3.0um	
Top Vias	(Dense)	sparse	**none**			
MT(-1)	sheet	dummy fill	wide slots	large holes	small holes	no metal
MT(-2)	sheet	dummy fill	wide slots	large holes	small holes	no metal
MT(-3)	sheet		wide slots			no metal

Interconnect layers' metal pattern "density" in the pad window = 100% for a full sheet, or reduced density values when slots or holes are placed in the metal, or 0% for no metal at all in the pad window.

The effect of a full metal sheet below pad window (ignoring top vias)

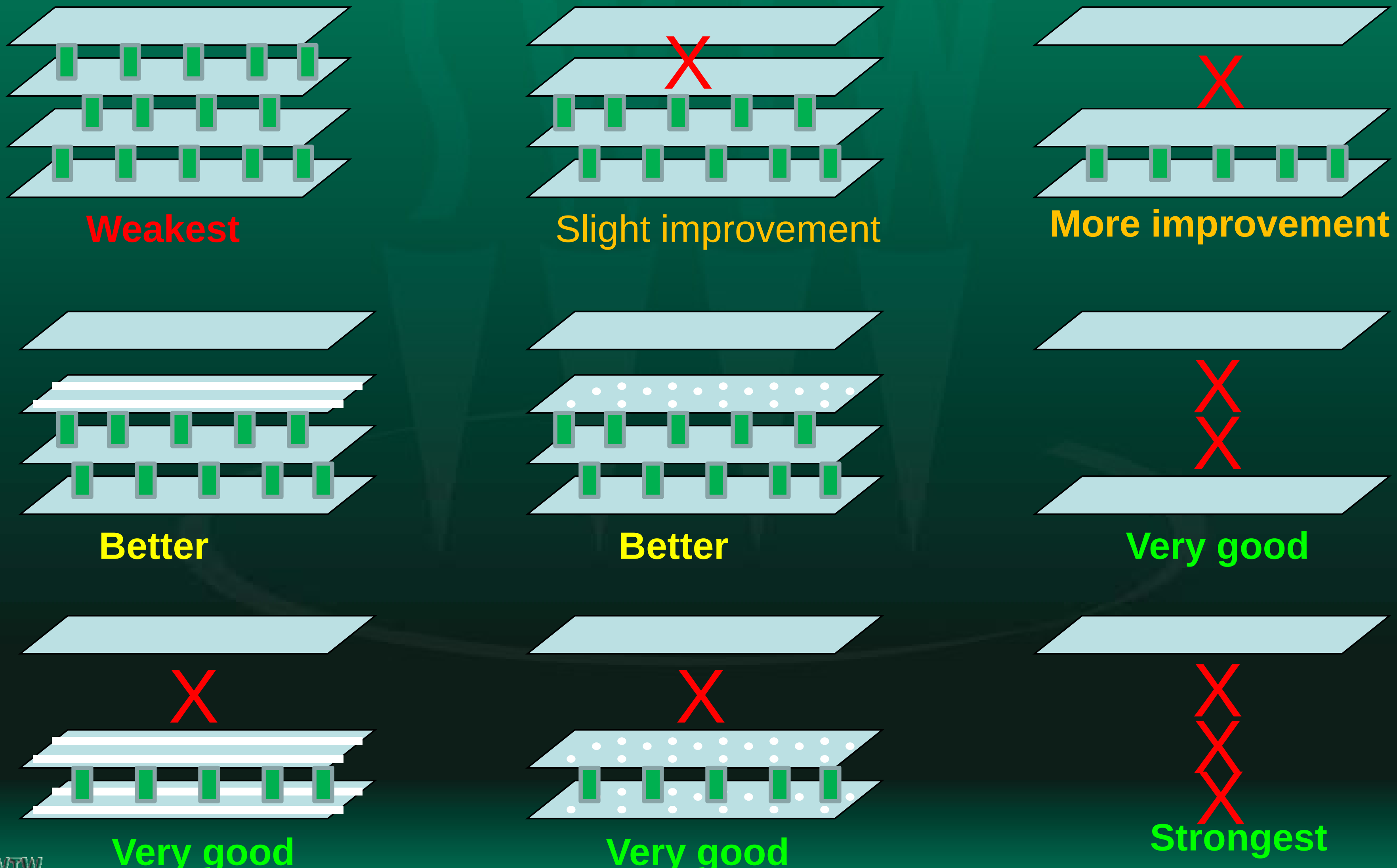
- **Ripple effect from probing is seen "worst" anytime there is a full sheet of metal beneath the pad window**
- **Cracking occurs "worst" anytime there is a full sheet of metal**
  - MT(-1) sheet: largest ripple, and highest % pads cracked
  - MT(-2) sheet, missing or pattern in MT(-1): reduced ripple, and order of magnitude fewer pads cracked
  - MT(-3) sheet, missing or pattern in MT(-1, -2): further reduced ripple, and another order of magnitude fewer pads cracked

Ripple effect from wafer probe

- **ripple effect seen in cratering test, due to underlying Al deformation and bending of SiO_2**
- **(often has the appearance of ripples on a pond)**
- **the pad on the right has slots in MT(-1): no ripple, and greatly reduced cracking tendency**
- **ripple effect correlates well with cracking**
- **ripple is best observed with differential interference contrast (DIC) microscope**

ripple effect is only visible on the 6 pads having full metal sheets below

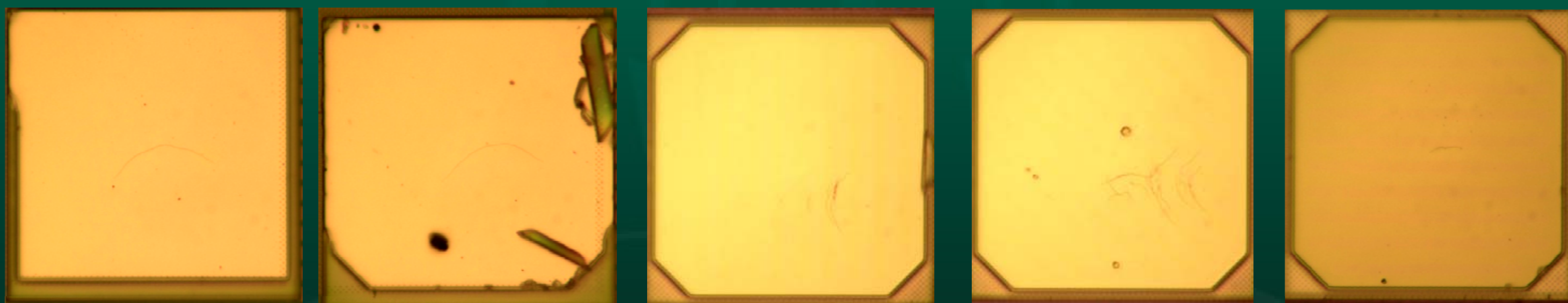
Summary Bond Pad Structure Cracking Results:
6 touchdowns at 4mils overdrive



MT(-1) experimental design examples

- **After cratering test, cracks are visible in the TiN barrier**
- **MT(-1) patterns can be seen, after removal of pad Al and TiN barrier film**

Cracks visible after cratering test on various design examples

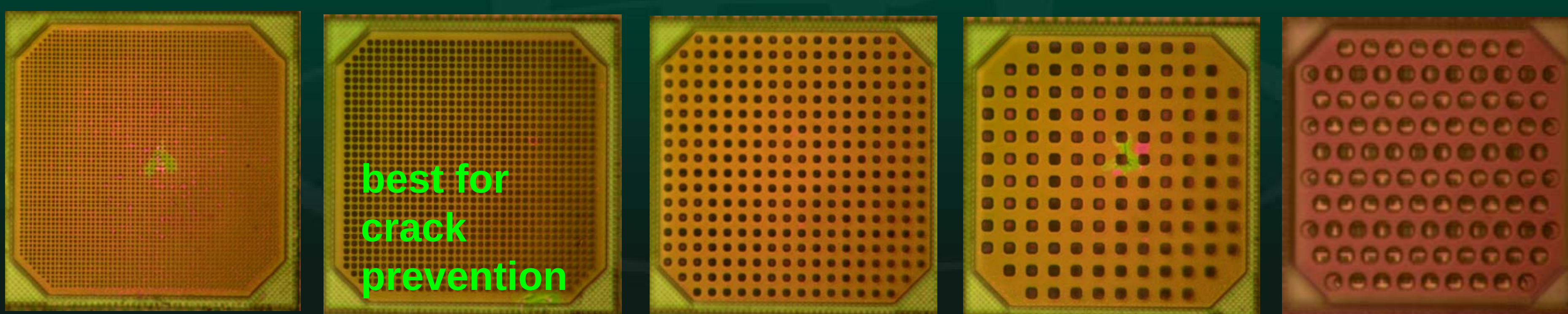


Extra cratering etch reveals MT(-1) patterns (not the same pads as above)

MT(-1) experimental design examples

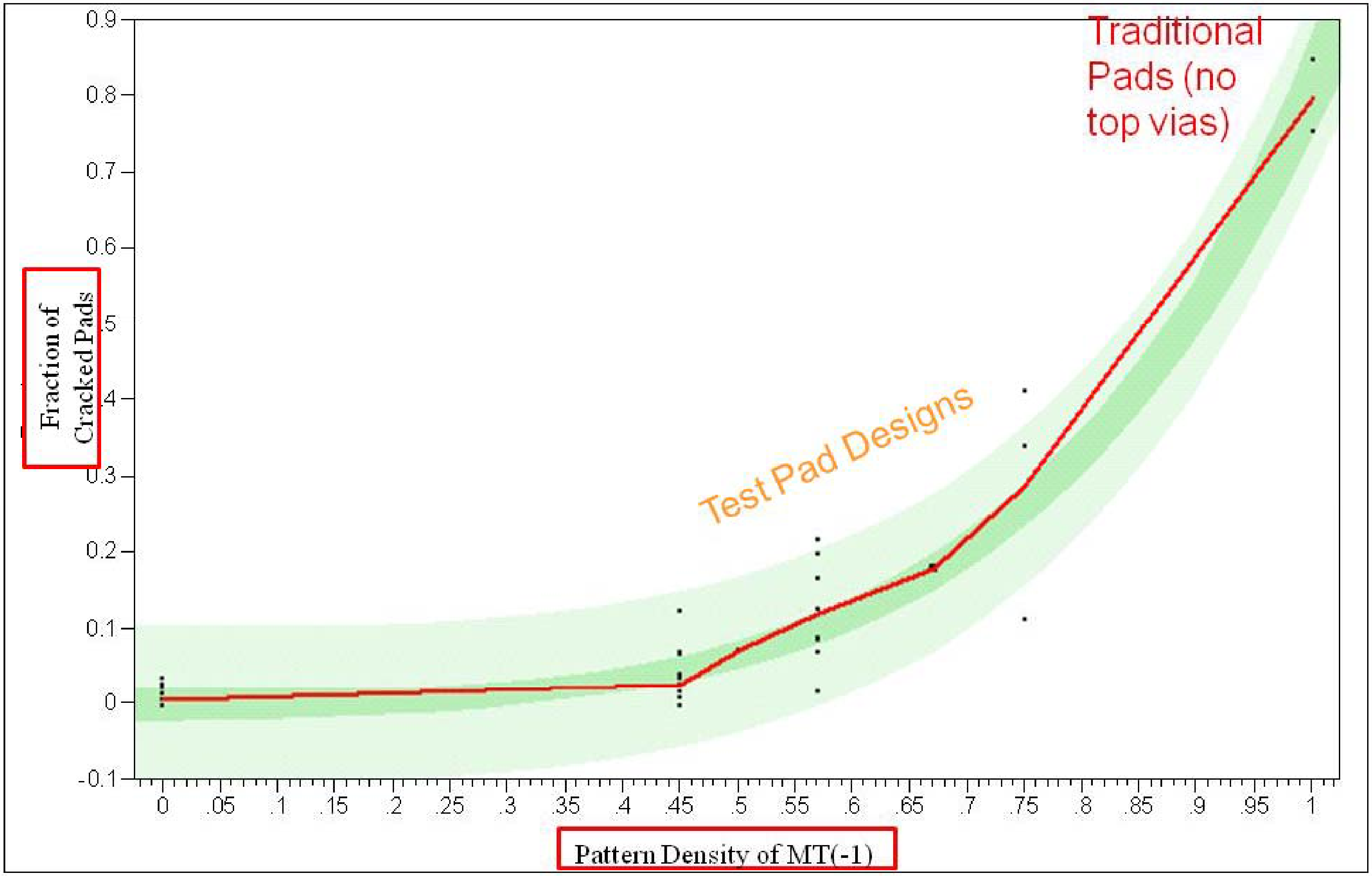
- **More MT(-1) patterns can be seen, after removal of pad Al and TiN barrier film**

Various MT(-1) patterns: arrays of holes

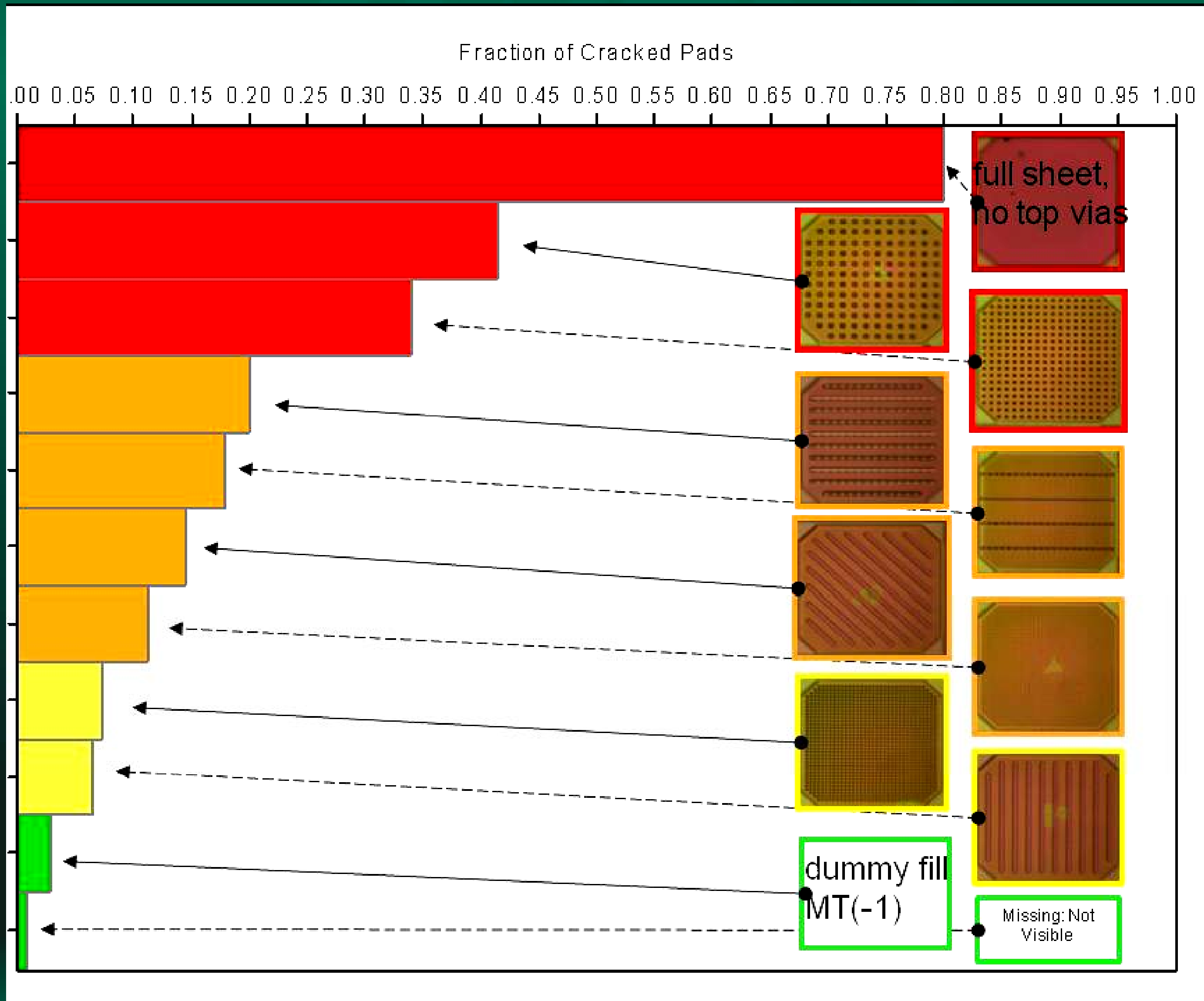


Harsh Probe Data Experimental Bond Pads

Fraction of Cracked Pads vs. Metal Pattern Density of MT(-1)

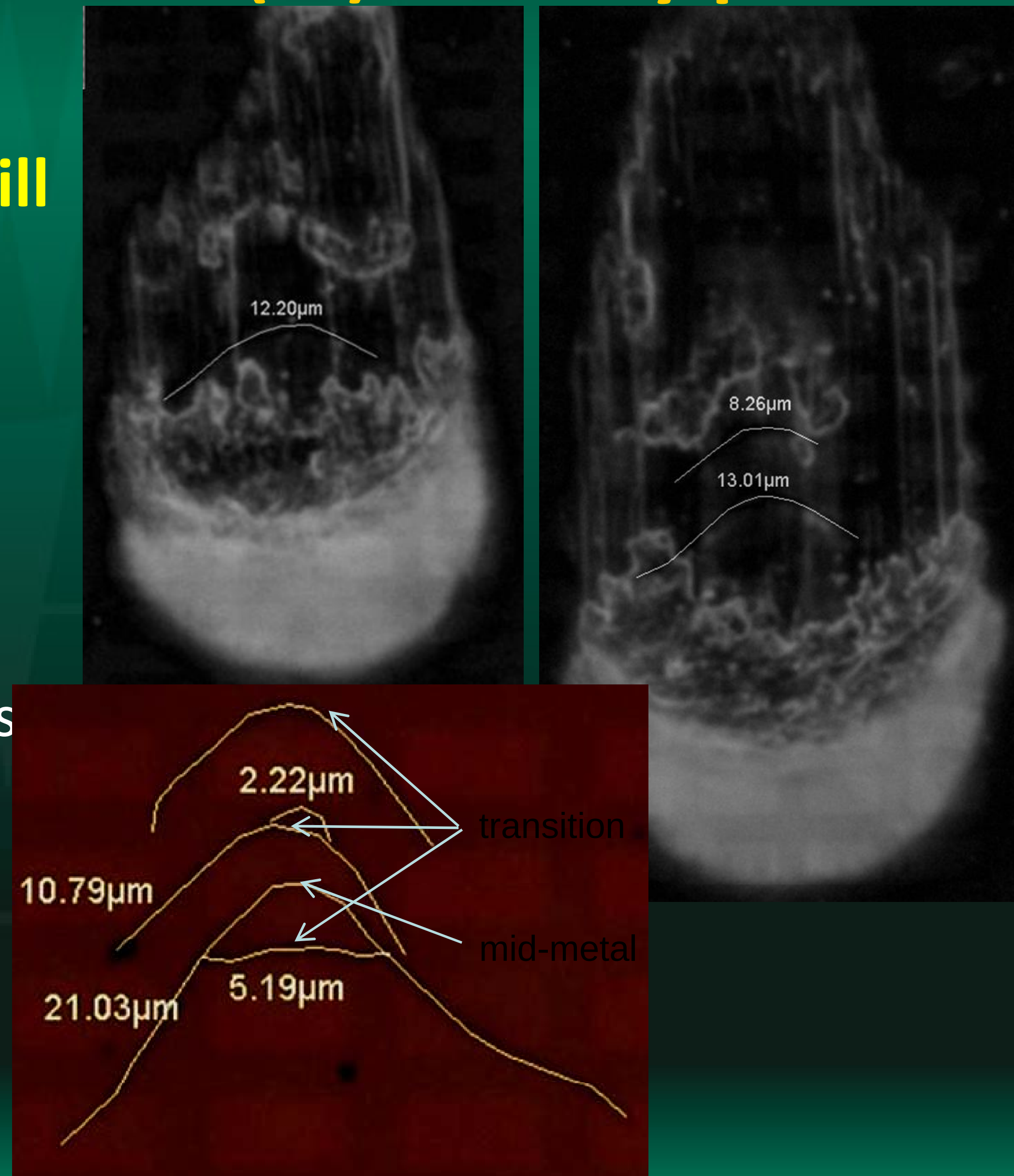


Pads cracked vs MT(-1) pattern



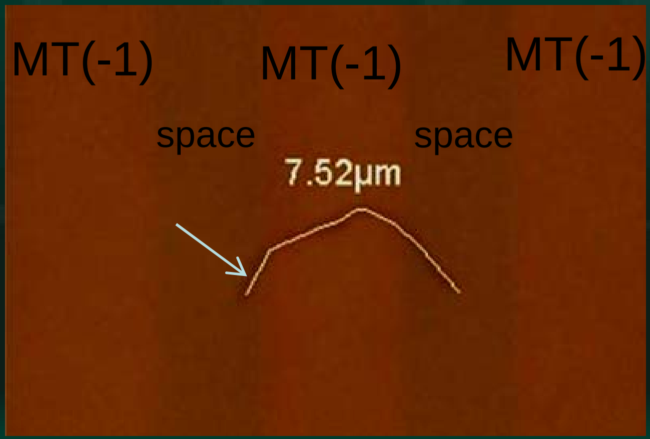
Crack interaction with MT(-1) dummy pattern

- **cracks from harsh probing with dummy fill pattern in MT(-1)**
- **cracks initiate at the transition of space to metal**
  - (the pattern is very difficult to see in photos but this interaction is observed routinely)



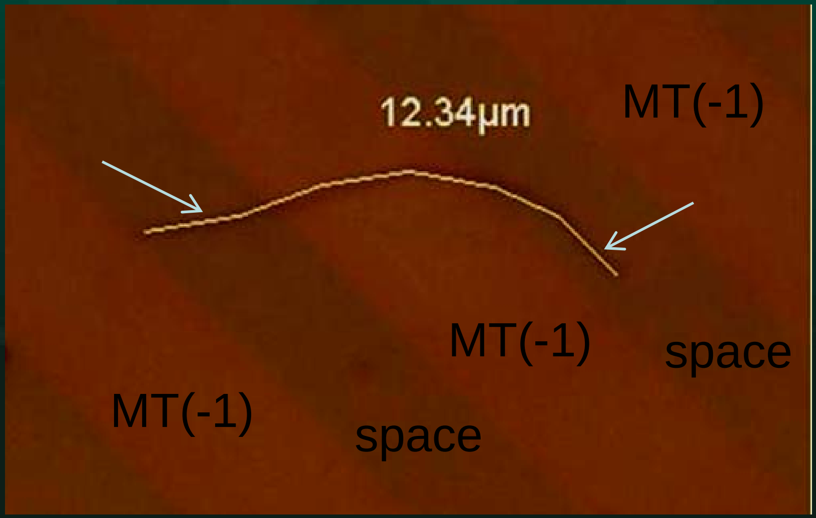
Crack interaction with slots

- **crack initiates above the metal (light orange)**
- **crack propagates normally until the edge of the metal**
- **propagation in the "space" changes direction**
  - tends to be more parallel to the metal edge



Crack interaction with diagonal slots

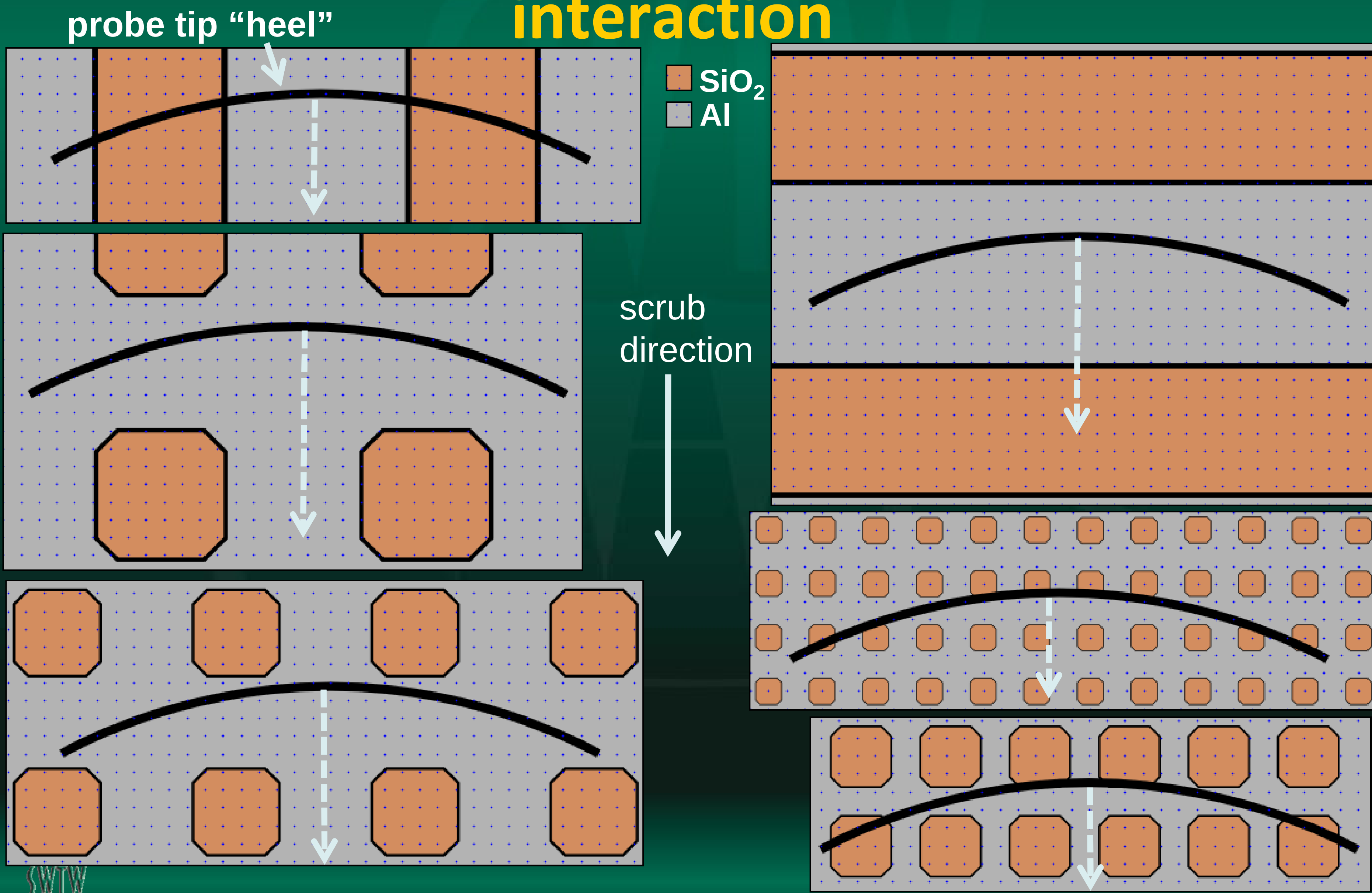
- **crack initiates above the diagonal metal (light orange)**
- **crack propagates normally until the edge of the metal**
- **propagation in the "space" changes direction**
  - tends to be either perpendicular or parallel to the metal edge



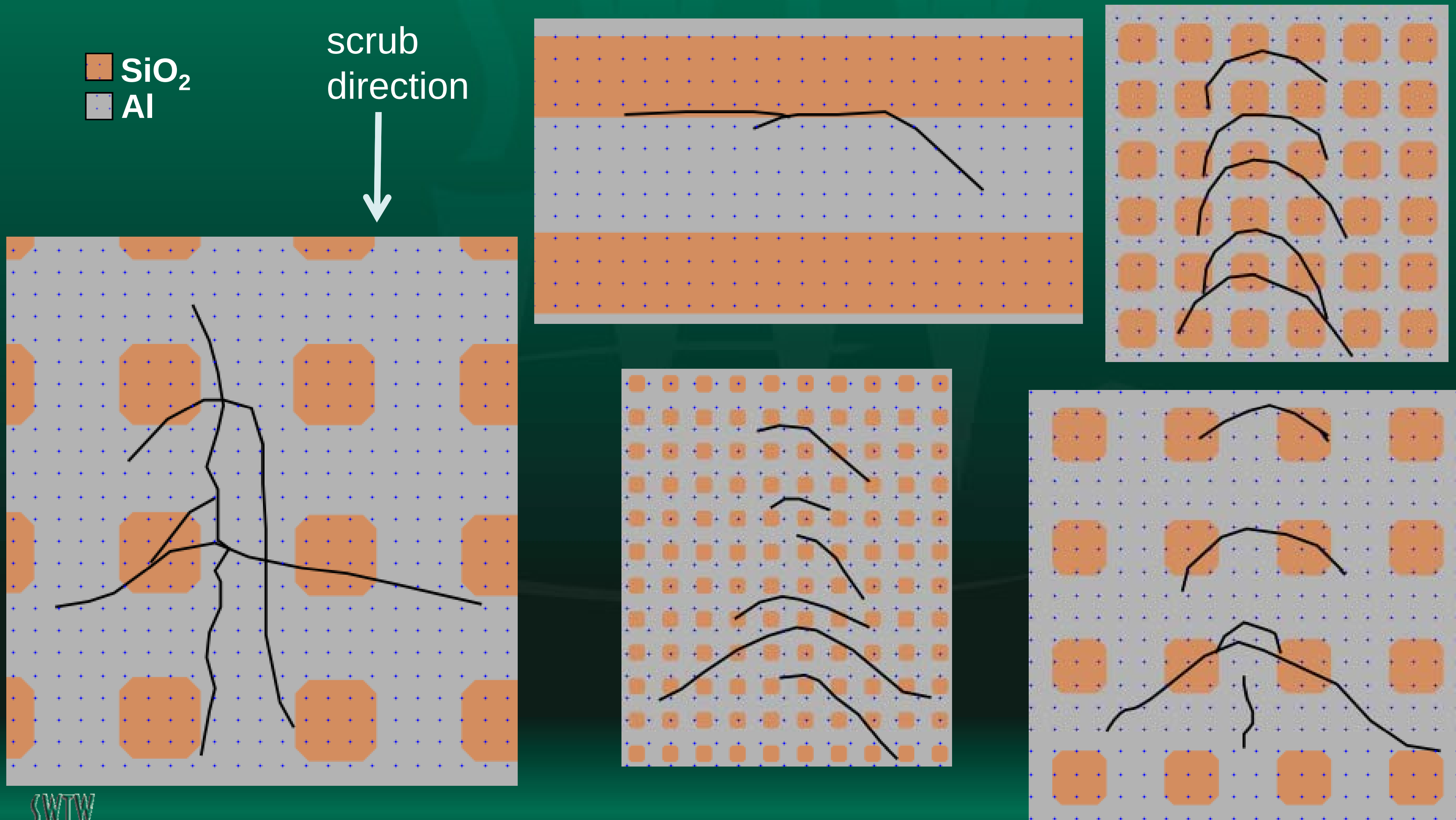
Discussion of results for harsh probing

- **factors of Overdrive, Touchdowns, and Probe Tip Length on traditional pads show the well known effects**
- **increasing pad Al thickness reduces cracks from harsh probing**
- **full sheet in MT(-1) appears to be a root cause of cracks from probe**
- **top vias weaken the SiO_2 even more and cause more cracking**
- **ripple effect tracks cracking – a witness of underlying films deformation**
- **cracking reduces when underlying metal density is lower, especially in MT(-1)**
- **cracking further reduces when MT(-1) width is small between spaces, slots or holes**
- **cracks interact with MT(-1) pattern**

illustrations to explain probe-pattern interaction



Illustrations to show actual crack interaction with MT(-1) patterns



What causes the cracks ?

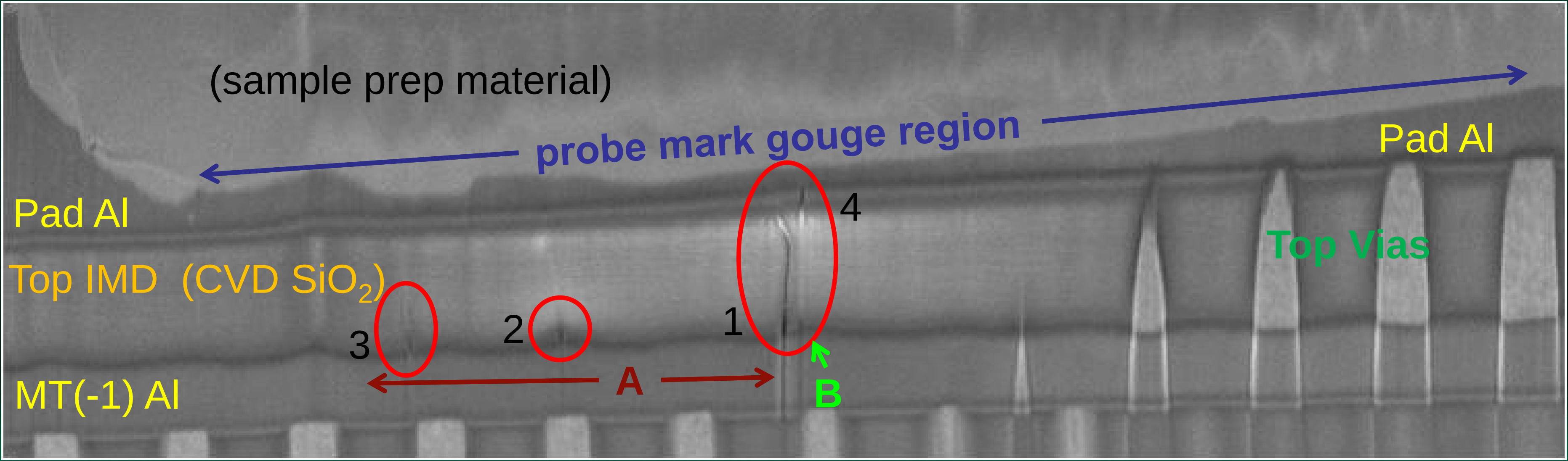
Proposed cracking mechanism:

- **1.) A predominantly downward force from the probe causes the pad Al to undergo plastic deformation (the probe mark) when its yield strength is exceeded (Al is weak in compression).**
- **2.) Some of the probe stress reaches the top dielectric and any top vias in the vicinity.**
- **3.) The SiO_2 will compress elastically like the Al, having a similar elastic modulus, but the W vias will not due to the much higher elastic modulus, resulting in extra local stress within the SiO_2 at the top via positions. SiO_2 is strong in compression and would not be expected to yield (crack) from the downforce unless it is allowed to bend.**
- **4.) Probe stress that reaches the MT(-1) will compress the Al elastically (and plastically if high stress) into a local "valley" (with local "hills" forming nearby due to the displaced Al material). The deforming Al of MT(-1) is expected to absorb the majority of the stress such that any films below it will not be deformed.**
- **5.) SiO_2 top dielectric bends into the "valley" of compressed MT(-1) Al, and a crack will easily initiate at the bottom due to the high tensile stress at that surface.**
- **6.) The crack or cracks may then propagate upwards in the SiO_2 during probing or in later processing or thermal cycling, breaking the upper SiO_2 surface and the TiN barrier to become visible in a "cratering test".**

Crack initiation from probing

Proposed crack mechanism

1. **region A films in compression during probe scrub**
   – cracks 1, 2, 3 initiate at bottom of SiO_2 film from high tension as SiO_2 bends in a "u" shape following the temporary Al "valley" in MT(-1)
2. **location B becomes a local maximum in MT(-1) Al thickness due to continued probe scrub action**
   – crack 4 initiates at top of SiO_2, cracking the pad barrier with it, due to high tension as the SiO_2 bends over the Al "hill"



Potential applications ?

- Possible to design new pads which are physically much more robust to cracking from wafer probe
- Simple design rules can be developed for BOAC interconnects
  - restrictive rules for MT(-1), but still allow free-form design
  - less restrictive rules for metal layers below
- BOAC design under the pad may be done with higher confidence when cracking mechanism is understood, and principles followed
- BOAC can use MT(-1) for circuitry
- “pad anywhere” may be feasible where the design rules are met
- Experimental results have much implication for wirebond, including harsh bonding such as Cu wire, without the need for very thick pad Al

Prevent cracks from probe by pad design

>>> don't let the SiO_2 "bend" significantly during probe <<<

1. **prevent high stress in the SiO_2 under pad metal**
   – thicker pad Al
   – (low force wafer probe, minimize touchdowns)
2. **thicken the SiO_2 under pad metal**
   – omit MT(-1) from the probe region
3. **avoid Al beneath the SiO_2 under pad metal**
4. **prevent deformation in the Al beneath the SiO_2**
   1. prevent Al valleys and hills, prevent plastic deformation
   2. do this by lowering the metal pattern density and minimizing metal width between spaces, slots or holes
   3. more local SiO_2 strengthens the structure when in compression

Implications for Cu / lowK ?

- **Cu surrounded by SiO_2 has less ripple or cracking than the equivalent Al metallization due to its reduced ductility. This is the typical case for a Cu / lowK IC with redistribution layer(s) on top. The lowK material is down farther in the pad structure.**
  - This team has done few experiments with Cu / SiO_2
- **Cu surrounded by lowK is actually *opposite* to Al with SiO_2: Cu is the stronger material, and lowK is weak in both compression and tension.**
  - Pad structures in Cu / lowK IC's is an active area of research with much published info.

Summary

- **Harsh probing was used to evaluate pad structures of Al metallization in SiO_2 dielectric**
  - cracks increase for increased overdrive and touchdowns, or short probe tips
  - cracks decrease for thicker pad Al
  - traditional pad designs, especially with dense top vias, are the weakest structures in terms of resistance to crack formation
  - cracks are facilitated by the presence of a ductile material (Al) beneath SiO_2
- **Cratering test was used to obtain most data for the analysis**
- **Lowering the metal pattern density of interconnect metal layers below the pad window reduces cracking**
- **Cracking can be further reduced by limiting the metal width between spaces, slots, or holes**
- **BOAC pads robust to cracking from wafer probe can be free-form designed based on simple principles**
- **Pads may be robust enough for Cu wirebond without thick MT**

Future work ?

- **Need top vias for BOAC –**
  - should be feasible according to the proposed cracking mechanism, but more experimental data is needed: *planned*
  - modeling, simulations: *planned*
  - *BOAC design guidelines: (future presentation in preparation)*
- **"Harsh" Au wire bonding experiments, to simulate Cu wire bonding and other situations of interest**
  - *upcoming presentation* from same team: "**Use of Harsh Wire Bonding to Evaluate Various Bond Pad Structures**", IMAPS EMPC, SEP 2011
- **Can Cu wirebond on robust pad structures tolerate deeper or larger area probe marks?**
  - more experimental data needed
- **Use of the ripple effect to predict cracking / reliability**
  - *future presentation in preparation*

Acknowledgements

- **we gratefully acknowledge the significant contributions of many ON personnel, including**
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