



Micro Magnetics

Sensible Solutions

SERIAL NUMBER: 2044

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Scanning magnetoresistive microscopy for die-level submicron current density mapping

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Purpose

- **Introduce the technique of current density mapping**
- **Present illustrative results and discuss FA/FI applications of the method**
- **Discuss strengths and limitations of the technique**

Outline

Introduction to the technique

Front-side results

Flip-chip and package results

Discussion

Conclusions and Future Work

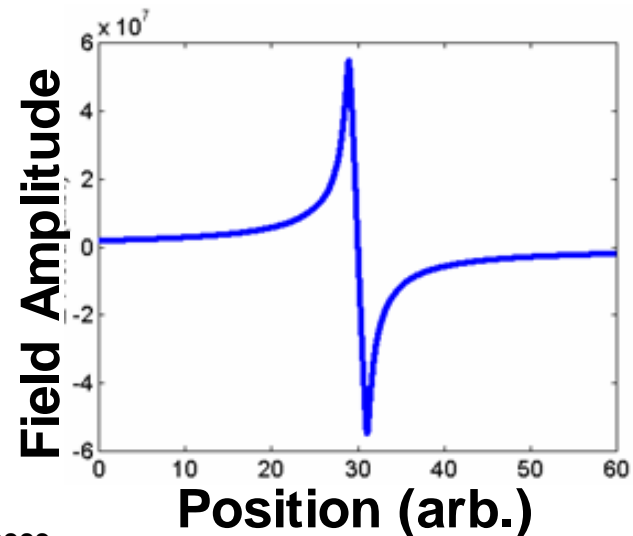
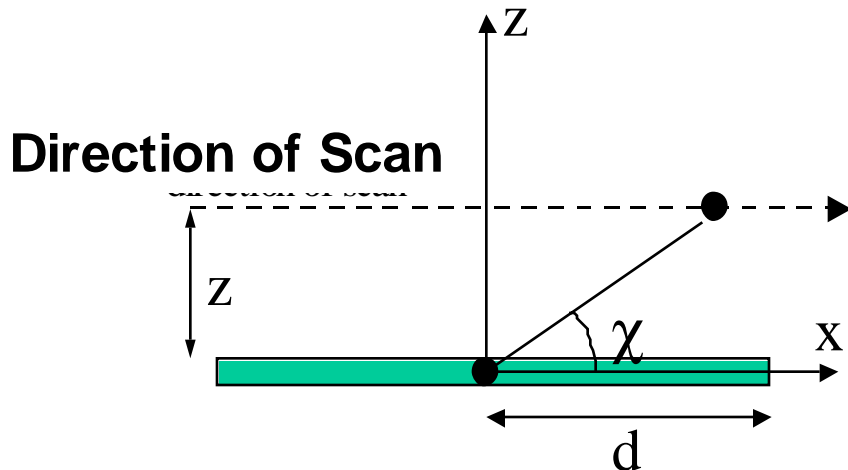
Magnetic Field Metrology for Integrated Circuits

A segment of wire dL carrying a current I creates a magnetic field:

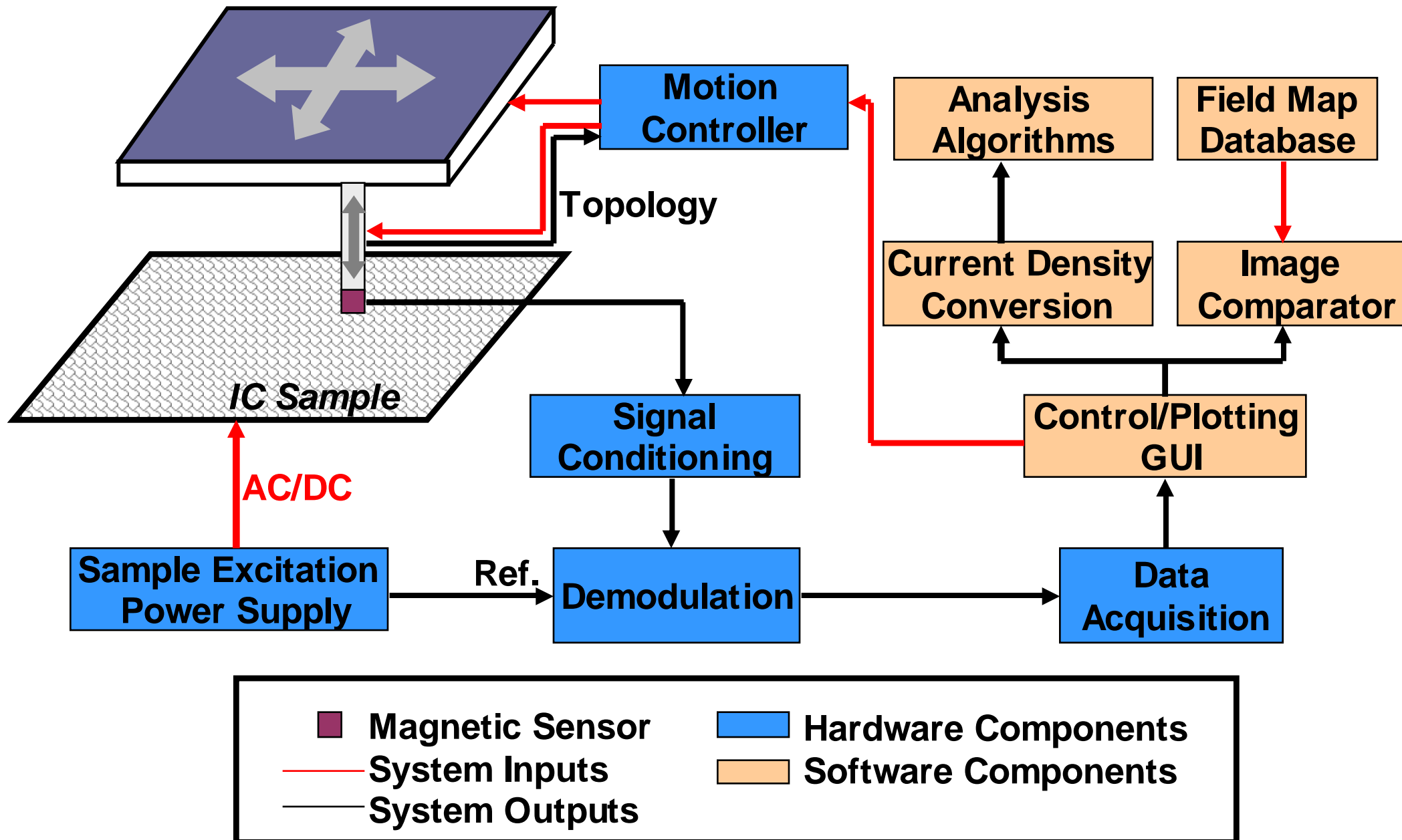
$$\vec{B} \propto \frac{\sigma_0 I dL \Delta \hat{r}}{4\pi r^2}$$

Finally, an infinite current-carrying stripe will create a field given by:

$$B_z(x, z) \propto \int_{-d}^d \frac{\sigma_0 I \cos \chi}{2\pi r} dl \propto \int_{-d}^d \frac{\sigma_0 (I/2d)(x - l) dl}{2\pi (z^2 + (x - l)^2)} \propto \frac{\sigma_0 I}{4\pi d} \int_{-d}^d \frac{u du}{z^2 + u^2} \propto \frac{\sigma_0 I}{8\pi d} \log \frac{z^2 + 2(x - d)^2}{z^2 + 2(x + d)^2}$$



System Block Diagram



Suggested looks of Circuit Scan Family



CIRCUIT SCAN CS1000



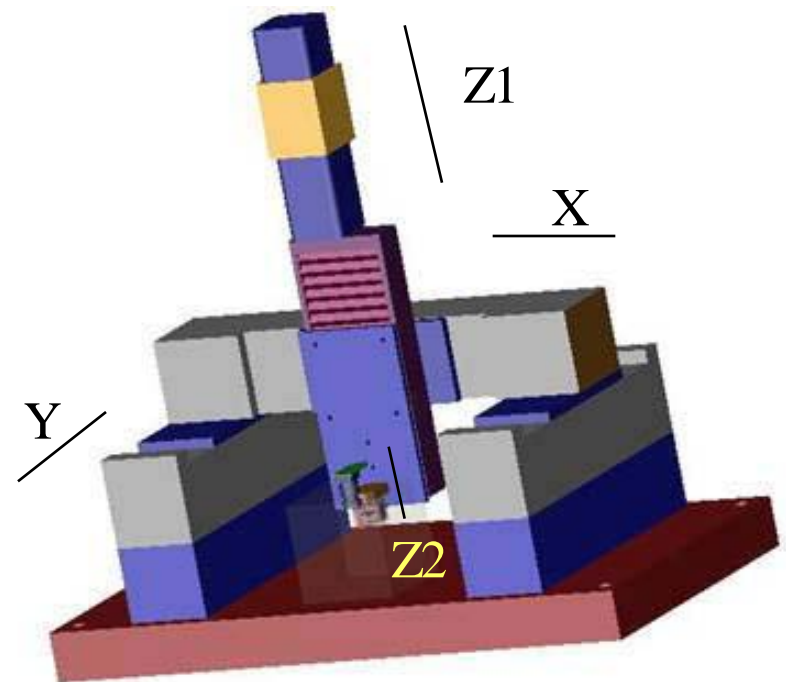
Machine Configuration



•Cartesian Machine with 4 AXIS

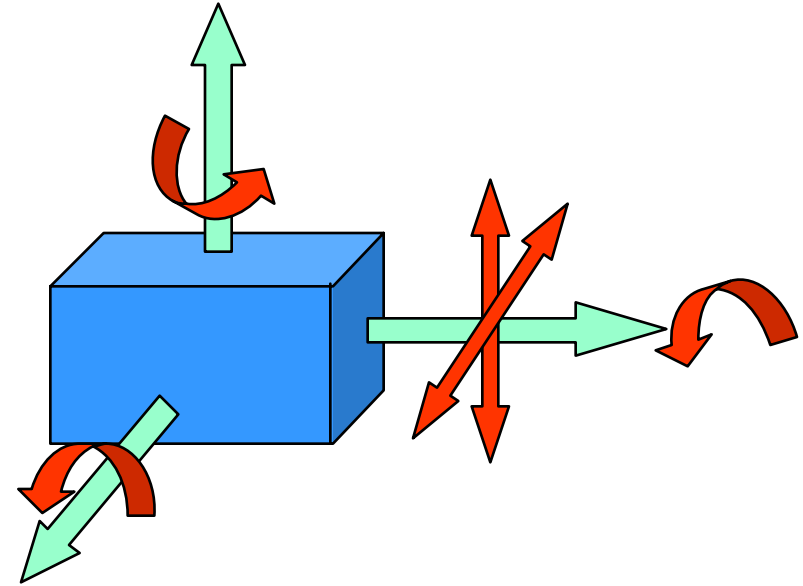
•Motion Details

X Axis	Step	100mm	10nm
Y Axis	Scan	100mm	10nm
Z1 Axis	Vertical	100mm	500nm
Z2 Axis	Sensor	0.2 mm	1nm



Error Motions

- Geometric
- Thermal
- Load induced
- Dynamic



- Geometric Errors (total of **21 errors** for 3 Axis machine)

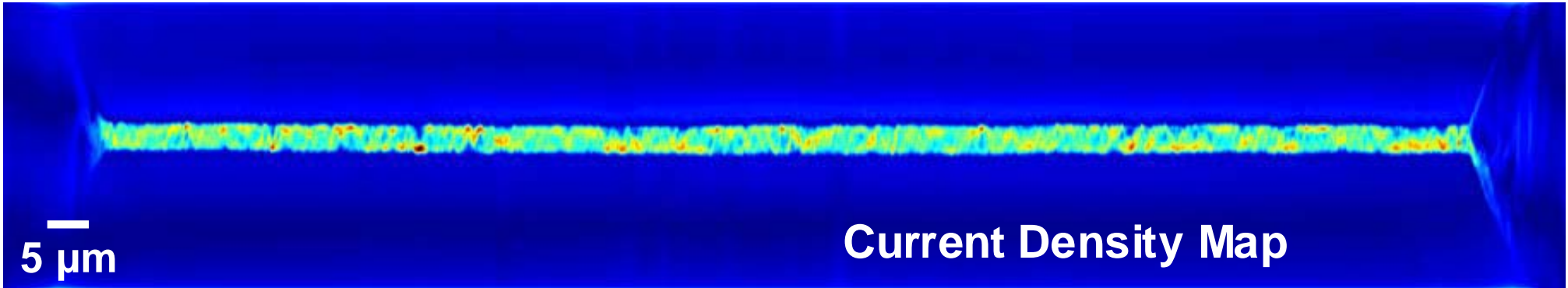
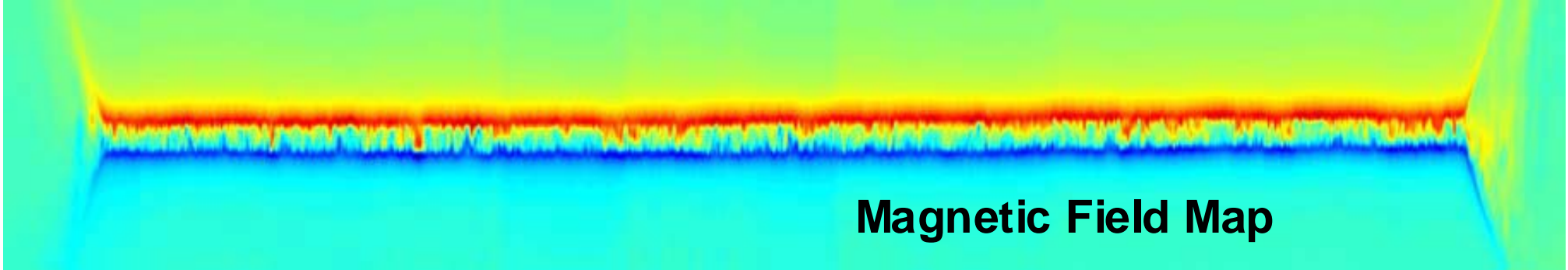
Translational Scale Error – 1 Straightness – 2

Angular Roll, Pitch, Yaw – 3

Squareness with other two axes – 2

Good News!! – For a deterministic machine these errors can be measured and compensated.

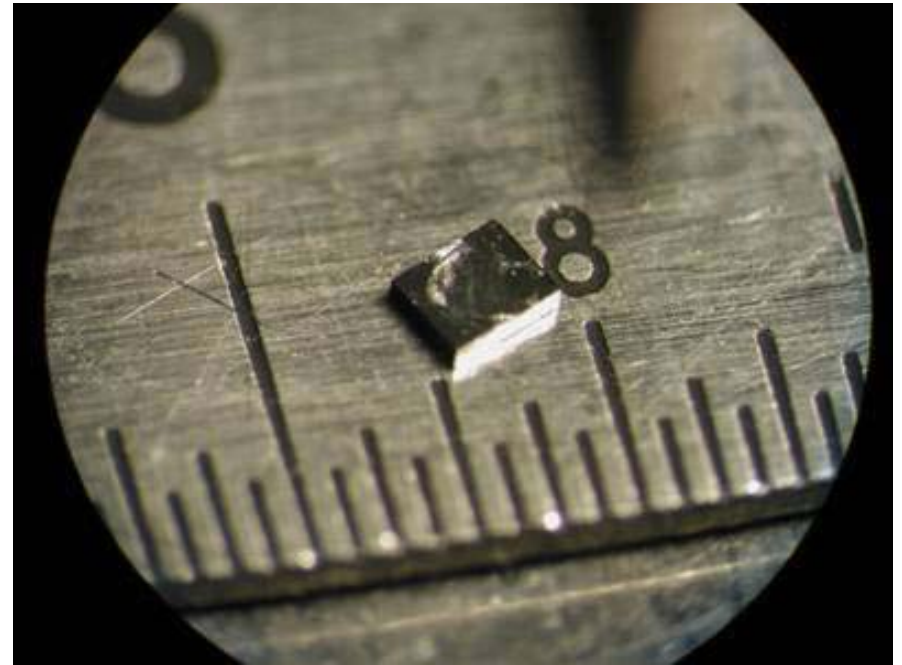
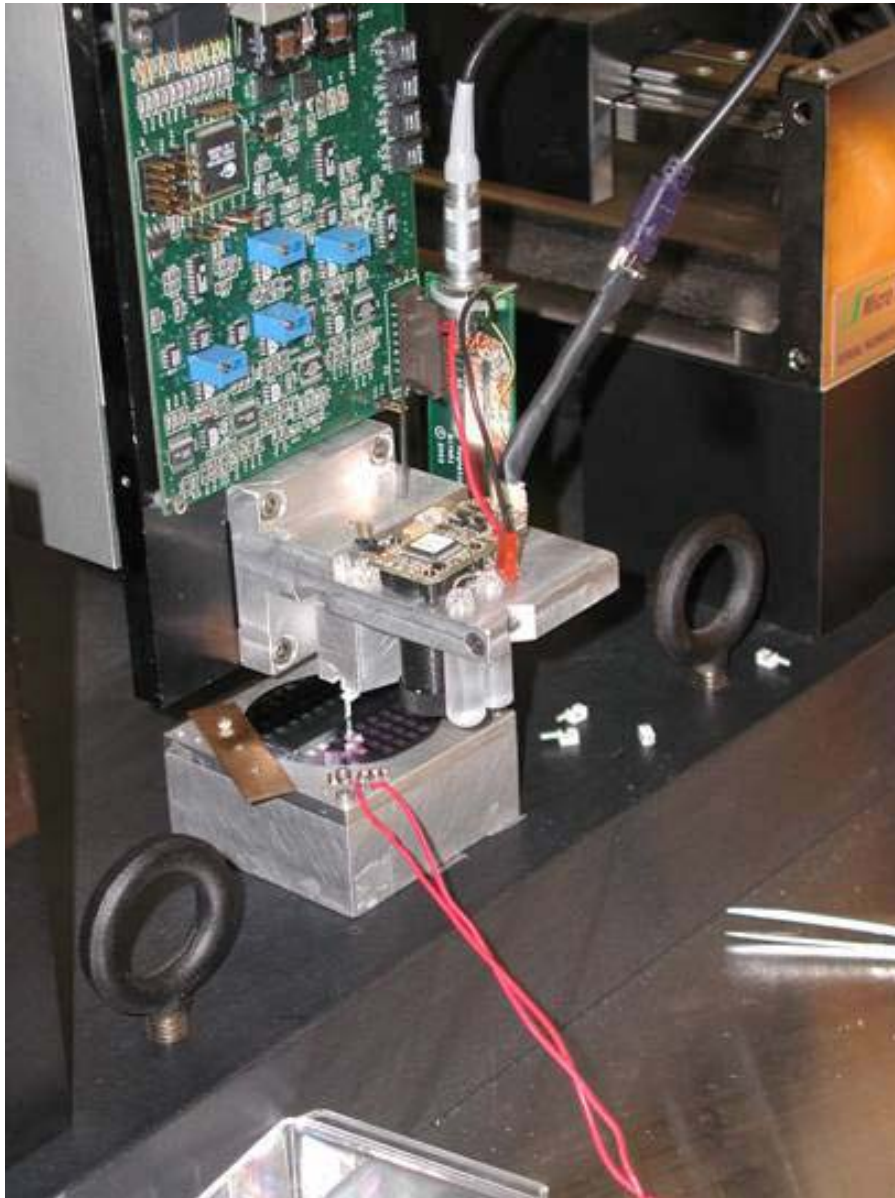
Sample Results



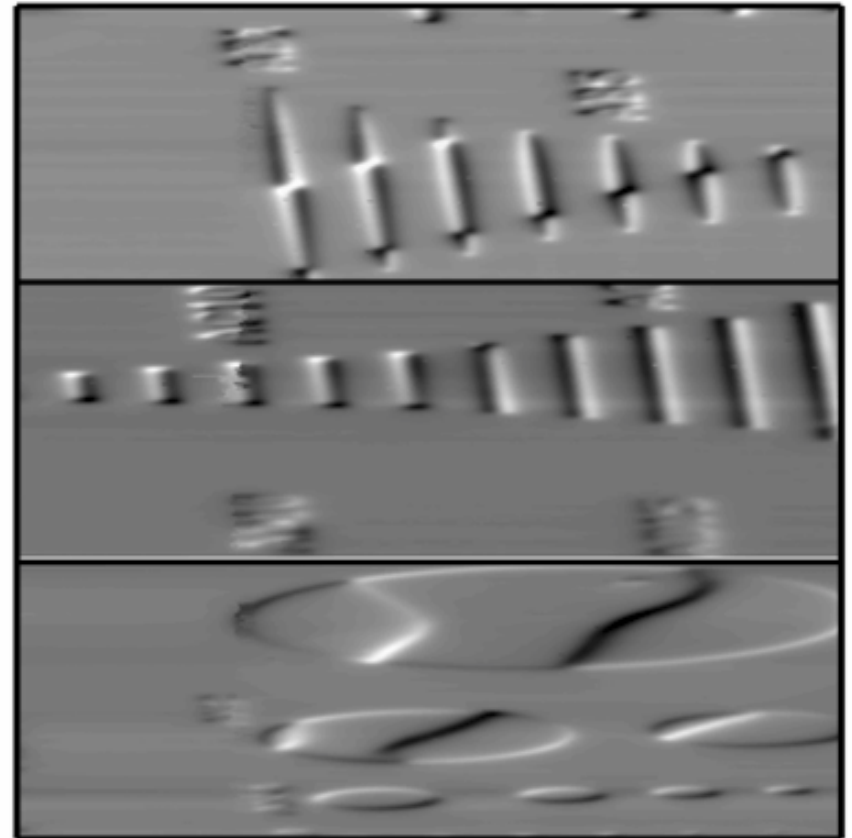
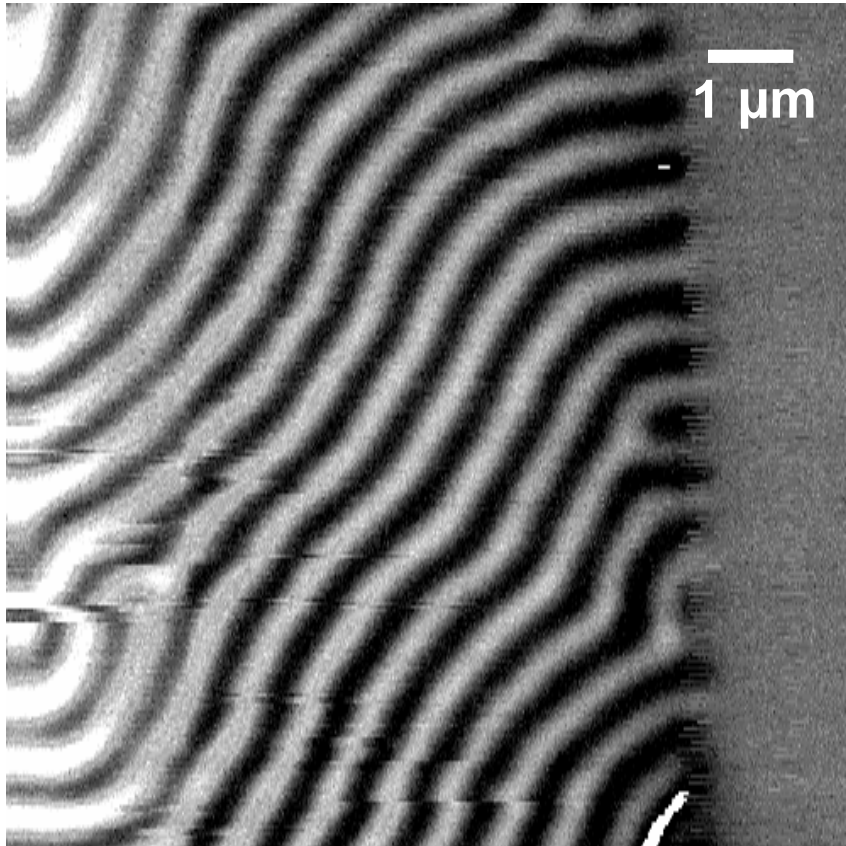
Notes on the technique

- **Non-invasive, non-destructive**
- **Unaffected by any non-ferrous overlayer**
- **Operates under ambient conditions**
- **Spatial resolution better than 50 nm**
- **Can detect currents as small as 1 μA**

Sensor



Sensor Footprint – 1 X 1.3 mm



DC imaging: GMR (left) and MTJ (right)

Comparison of different techniques

Sensor	Field Noise (nT/rtHz)	Resolution (nm)	Frequency Range (MHz)	Special Environmental Requirements
GMR ^{1,2}	30	100	DC to >1000	No
MTJ, available ³	0.3	5000	DC to >1000	No
SQUID ^{4,5}	0.03	30000	DC to 0.1	cryogenics
MTJ, proj. ⁶	0.3	200	DC to >1000	No

1 – Jury, et. al., IEEE Trans. Magn. **38** (5), 3545 (2002).

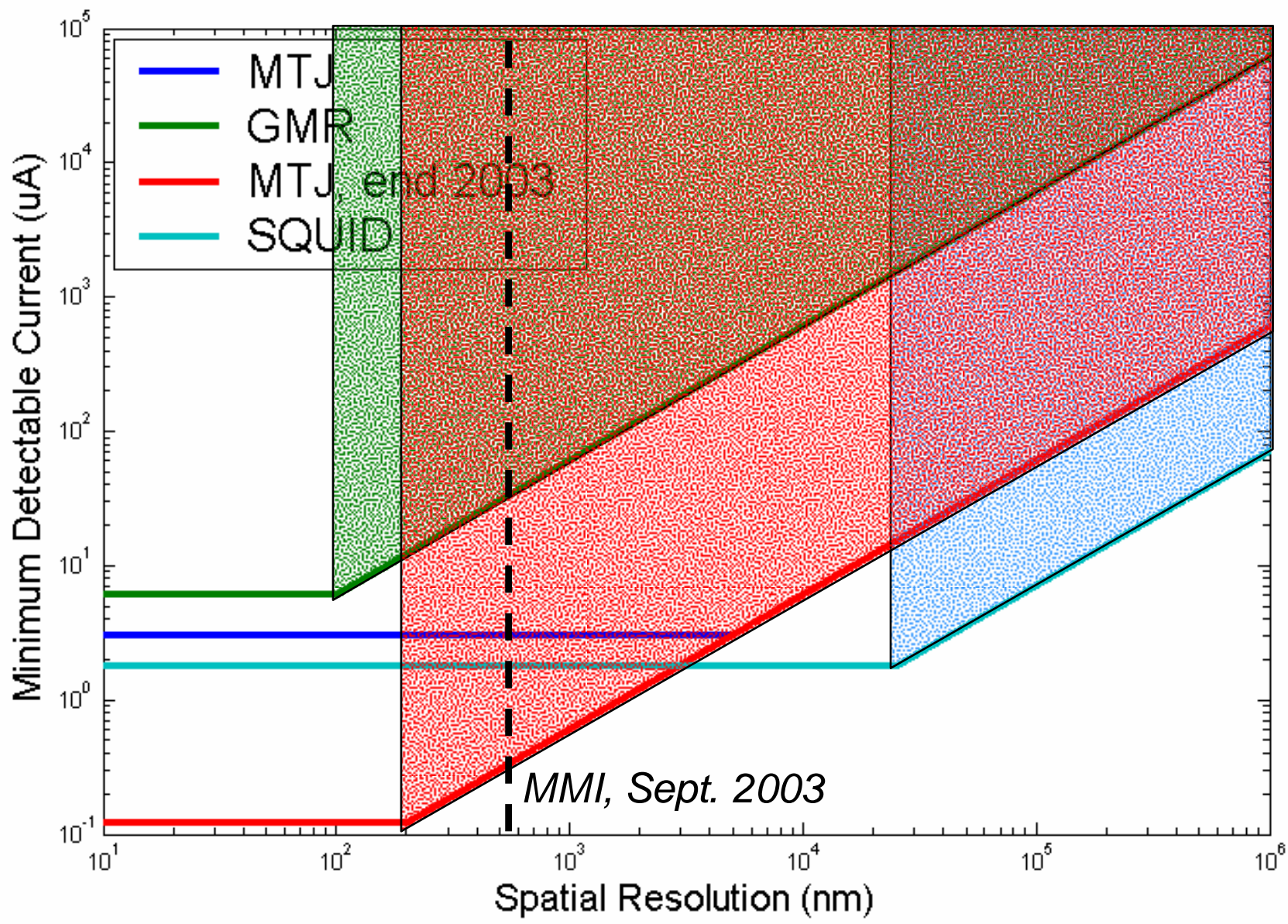
2 – MMI, unpublished.

3 – Liu, et. al., J. Appl. Phys. **92** (8), 4722 (2002).

4 – Chatraphorn et al., Appl. Phys. Lett. **76** (16), 2304 (2000).

5 – Kirtley, et. al., Annu. Rev. Mater. Sci. **29**, 117 (1999).

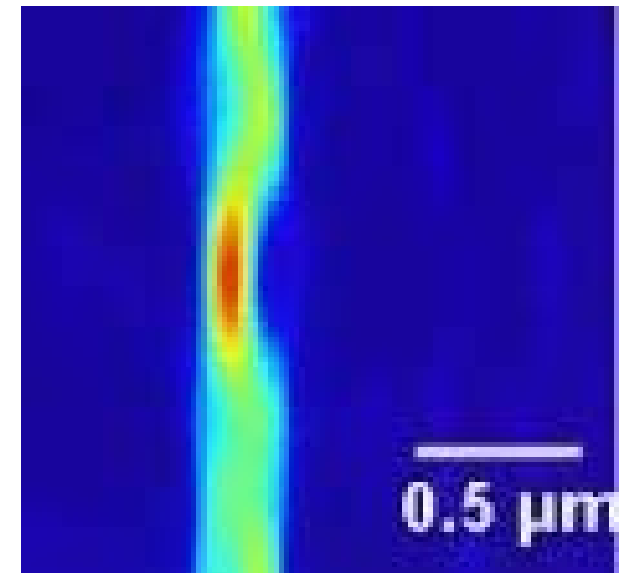
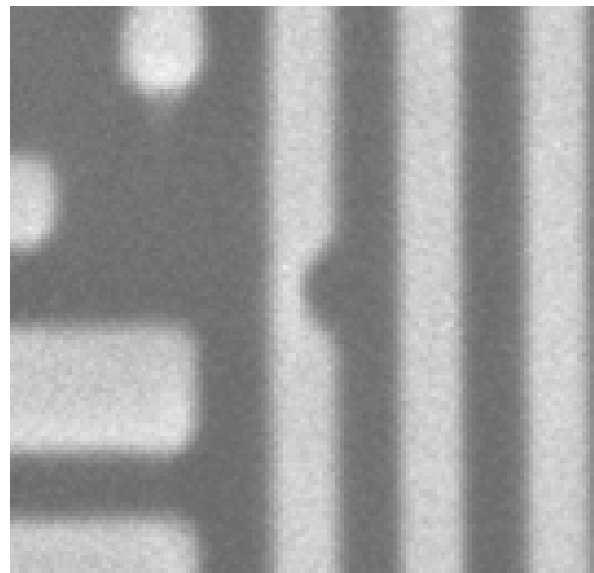
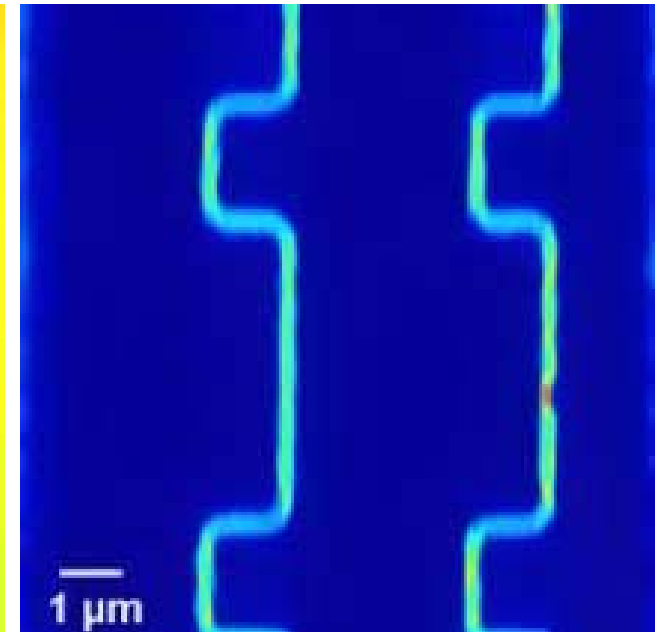
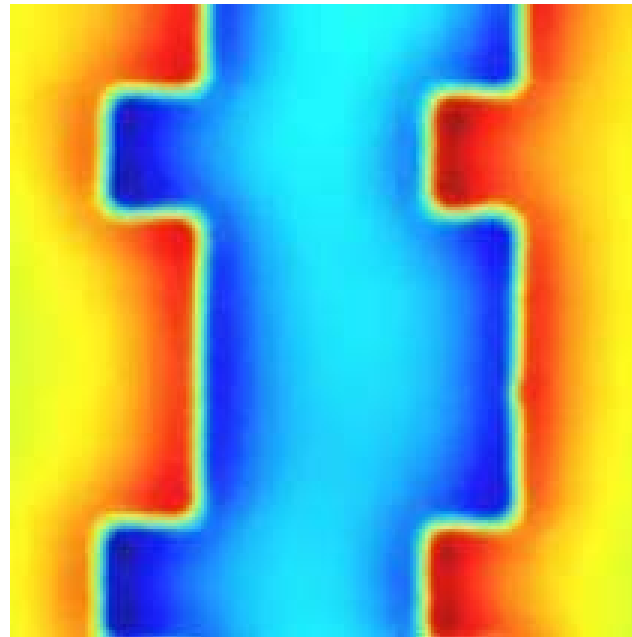
6 – MMI, unpublished. As of Sept. 2003, sensors capable of resolution of 500 nm have been demonstrated.



Results 1: 125 nm edge defects

*Quarter-micron pitch Cu
containing an intentional
edge defect with thickness
125 nm.*

*Current = 0.5 mA AC
Scan time = 5 minutes*

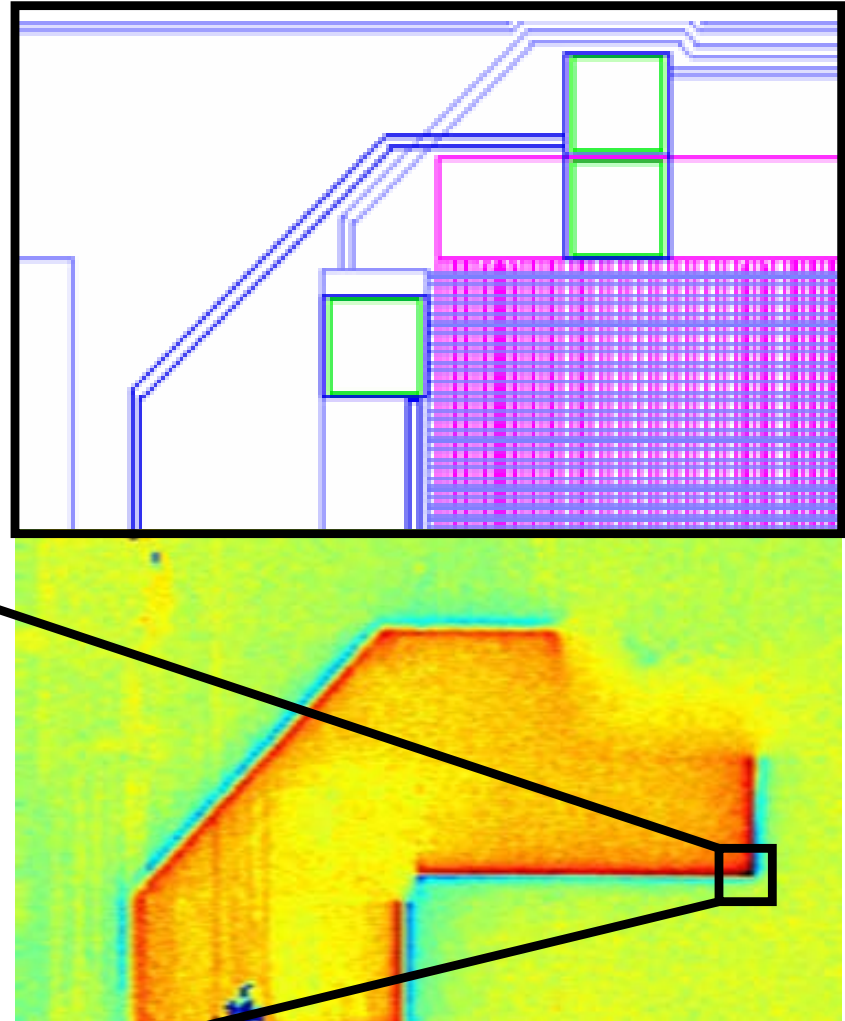
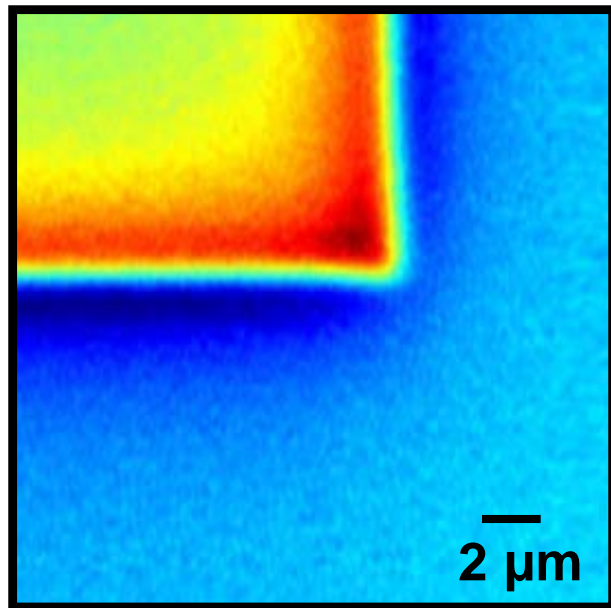


Results 2: Cross-point array failure

*Four-level Cu test structure.
Perpendicular arrays of metal
fingers on M1/M2 are separated by
a thin dielectric, creating an array
of potential failure sites.*

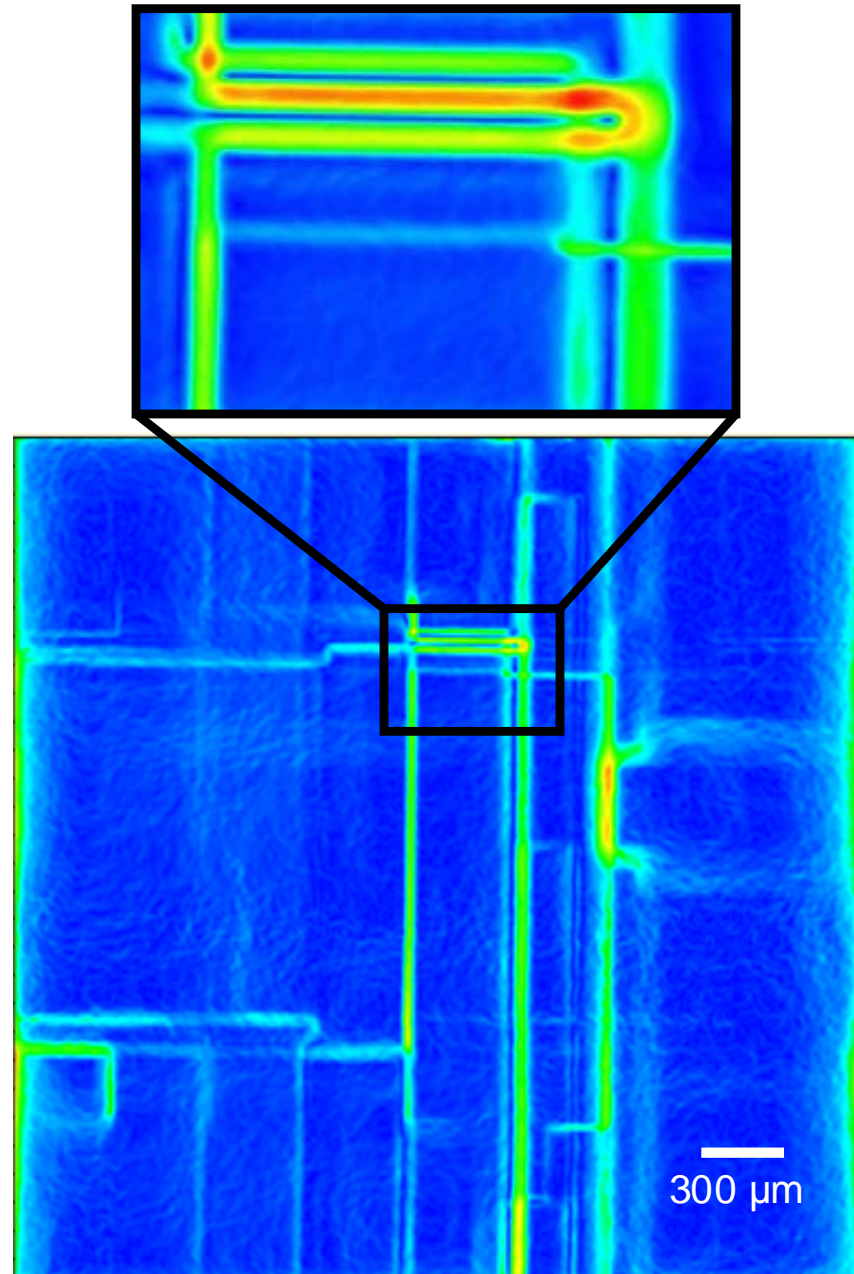
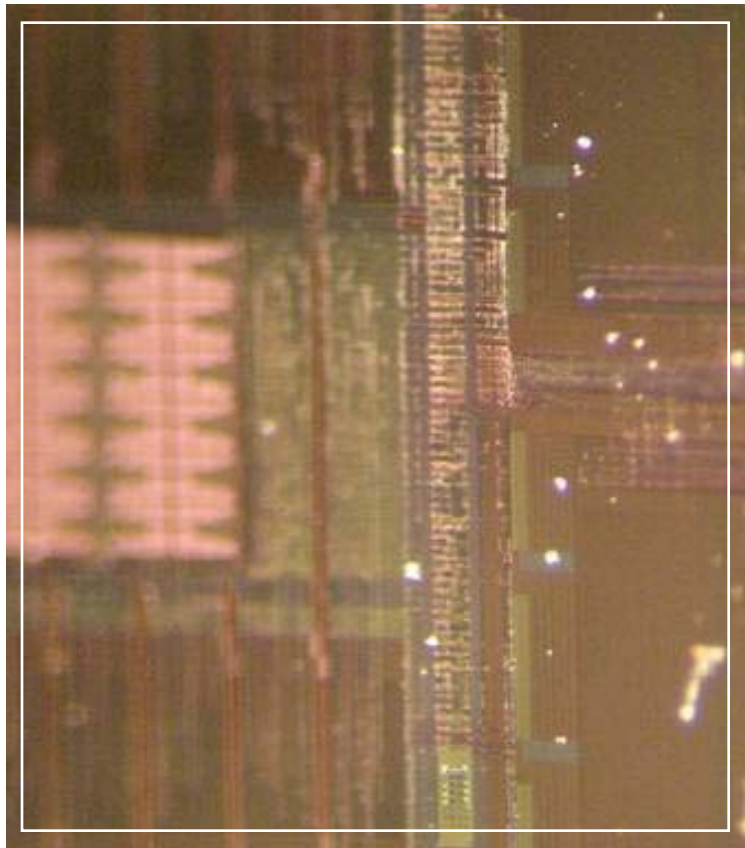
(Magnetic field images shown.)

the “leaky pixel”



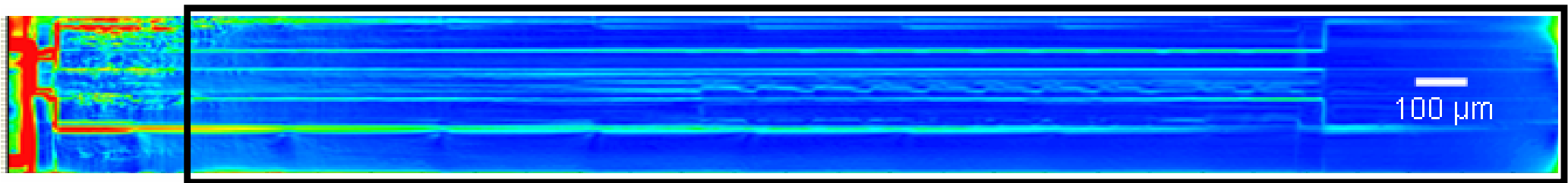
Results 3: Leaky logic chip

Operating logic chip powered at 1.4 V with 200 mV modulation signal.



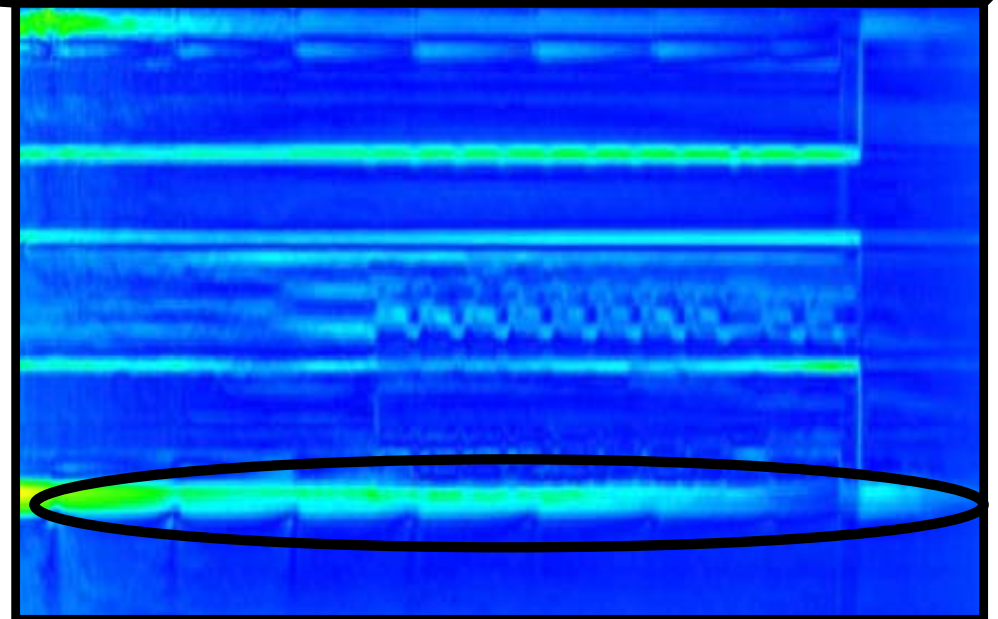
Results 4: Leaky SRAM device

Leaky SRAM device powered at 2.5V plus 200 mV modulation.

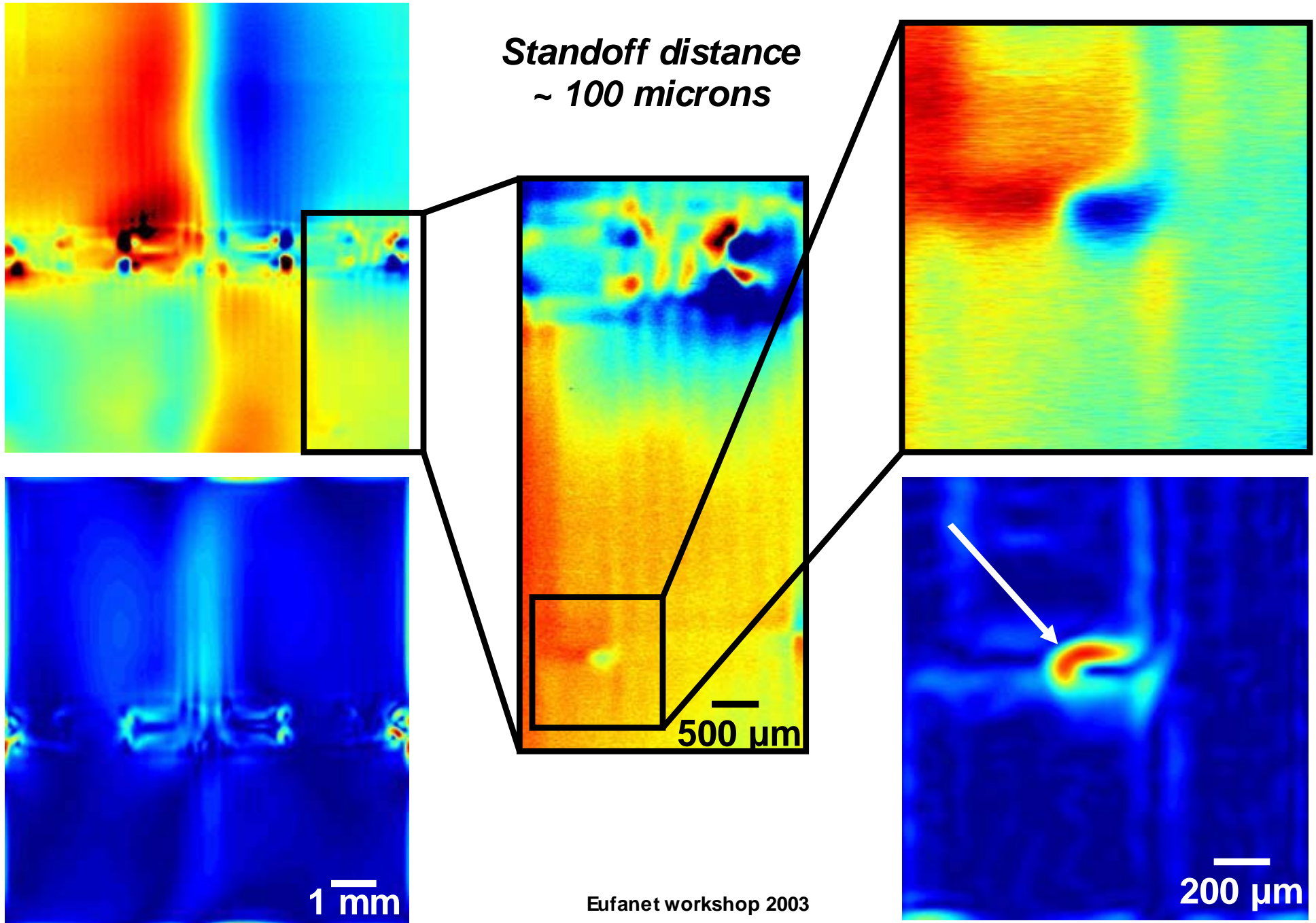


Above: Full scan at actual aspect.

Right: Skewed aspect ratio shows a gradually diminishing current flow as power is distributed



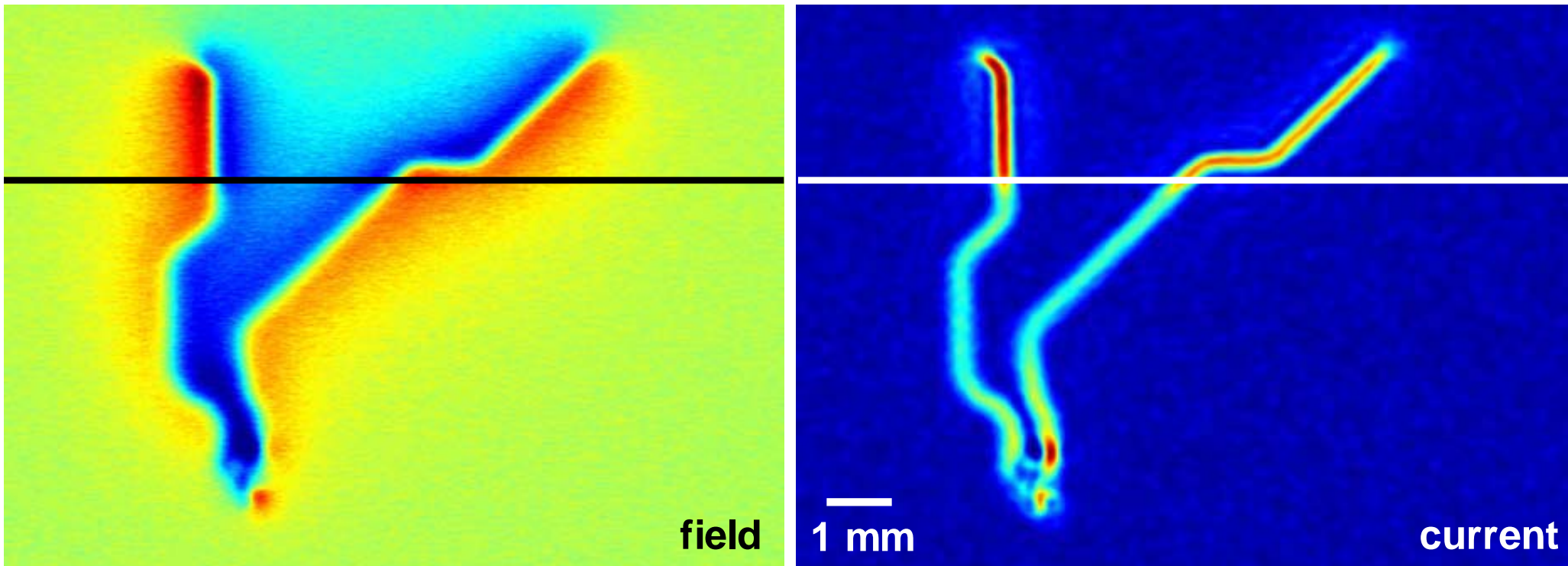
Results 5: Flip-chip with FIB-induced short



Results 6: Current flow in a package

*Current flow is through the package and onto the die.
(dividing line is indicated)*

$$I = 0.7 \text{ mA}$$



Discussion

- **Operating frequency should be chosen to ensure an accurate image. (Sensor response is linear from DC to GHz.)**
- **For complicated samples, image comparison might be the most efficient analysis routine.**
- **Analysis allows for “depth detection” of currents.**

Summary / Conclusions

- We have described a new current density metrology technique for FA/FI in integrated circuits.
- The instrument utilizes a novel spintronic magnetic sensor to image magnetic fields at the surface of the device.
- The technique is non-invasive, ignores nonferrous overlayers, operates at ambient conditions, and has spatial resolution < 50 nm.
- We have demonstrated results on several integrated circuit samples.

Thanks: Wayne Ford, C. L. Jan, Mike McIntyre, Dave Vallett, Zhiyong Wang

Future Work

- **High-throughput, high-resolution imaging for in-line applications.
(Advanced Technology Program, awarded Sept. 2003)**
- **Imaging of dielectric breakdown (today: magnetic tunnel junctions, tomorrow: IC applications?).**
- **Improve sensor sensitivity and continue miniaturization.**