Gurpreet Singh

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Scanning magnetoresistive microscopy for die-level submicron current density mapping

B. D. Schrag, Gang Xiao
Micro Magnetics Inc., Fall River, MA.

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

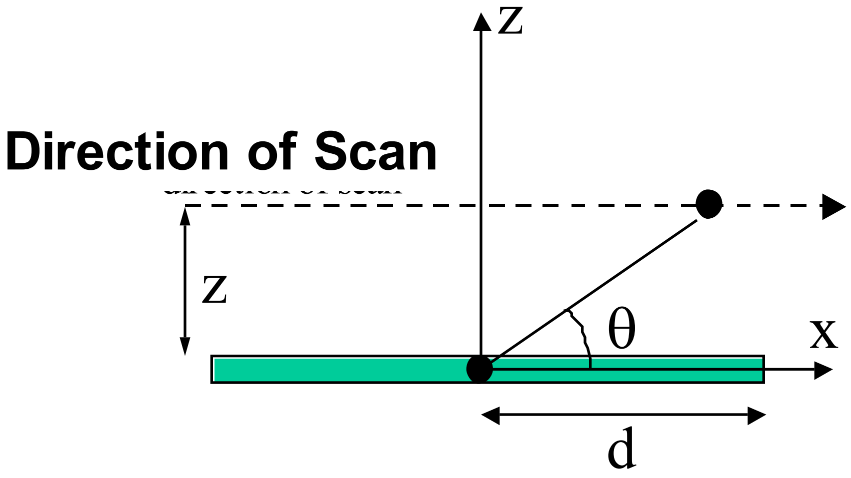
Magnetic Field Metrology for Integrated Circuits

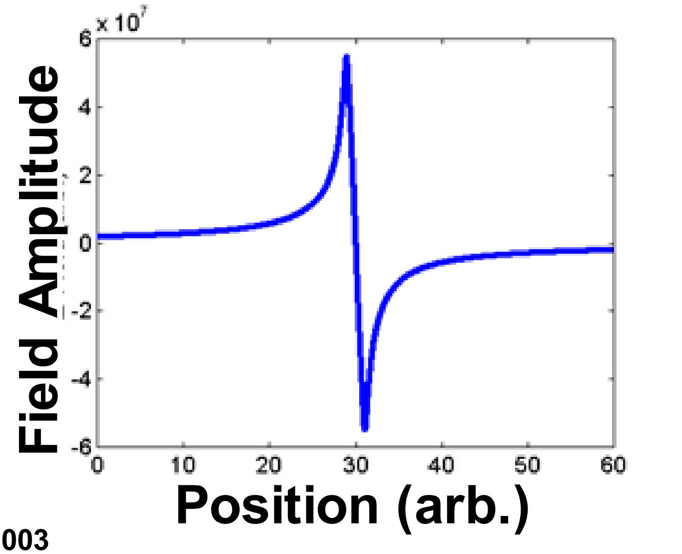
A segment of wire dL carrying a current I creates a magnetic field:

$$\vec{B} = \frac{\mu_0 I d\vec{L} \times \hat{r}}{4\pi r^2}$$

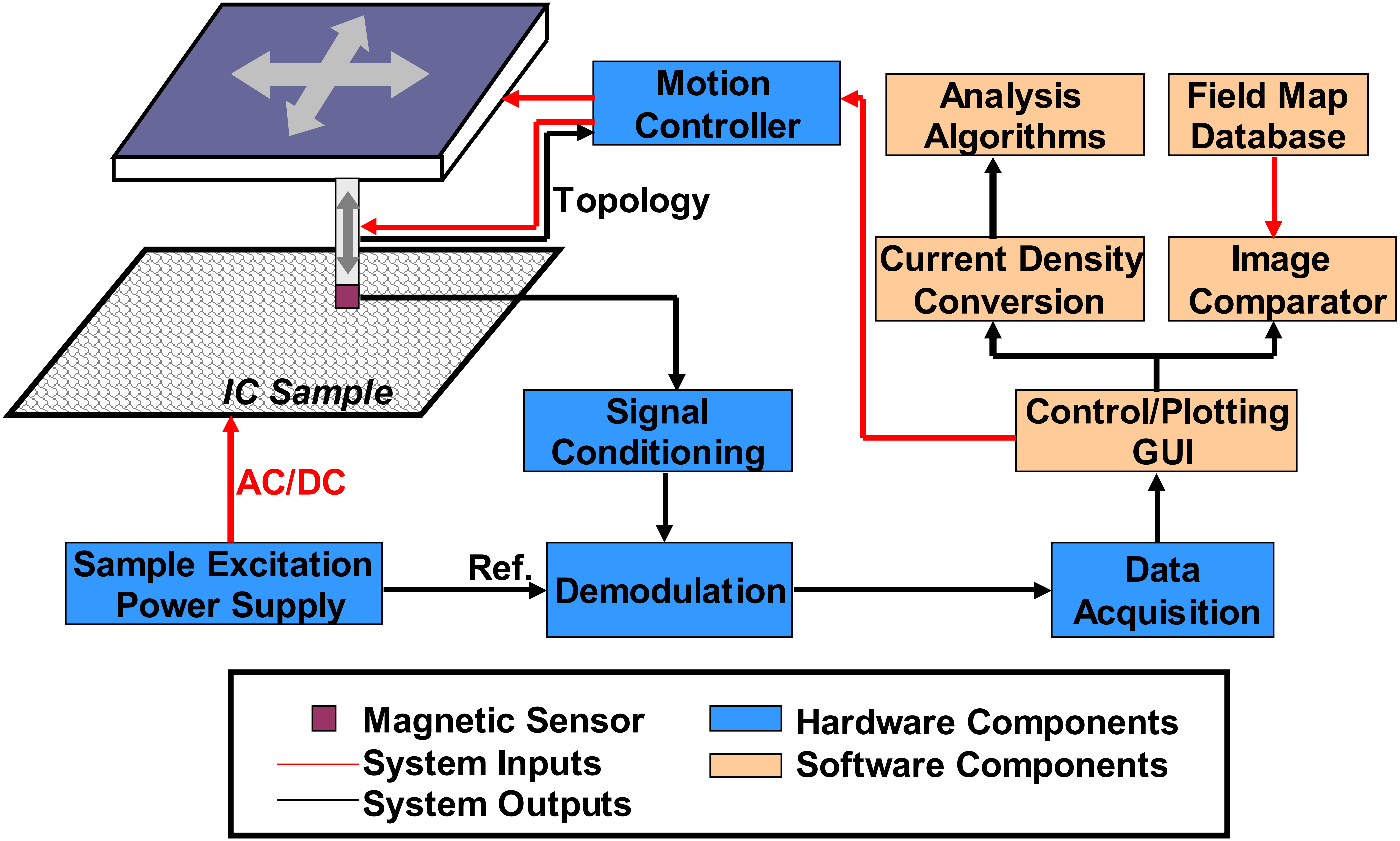
Finally, an infinite current-carrying stripe will create a field given by:

$$B_z(x,z) = \int_{-d}^{d} \frac{\mu_0 \lambda \cos\theta}{2\pi r} = \int_{-d}^{d} \frac{\mu_0 (I/2d)(x-l)dl}{2\pi(z^2+(x-l)^2)} = \frac{\mu_0 I}{4\pi d}\int_{x+d}^{x-d} \frac{udu}{z^2+u^2} = \frac{\mu_0 I}{8\pi d}\log\left(\frac{z^2+(x+d)^2}{z^2+(x-d)^2}\right)$$





System Block Diagram



Motion Controller

Topology

Analysis Algorithms

Field Map Database

Current Density Conversion

Image Comparator

IC Sample

Signal Conditioning

Control/Plotting GUI

AC/DC

Sample Excitation Power Supply

Ref.

Demodulation

Data Acquisition

■ Magnetic Sensor

— System Inputs

— System Outputs

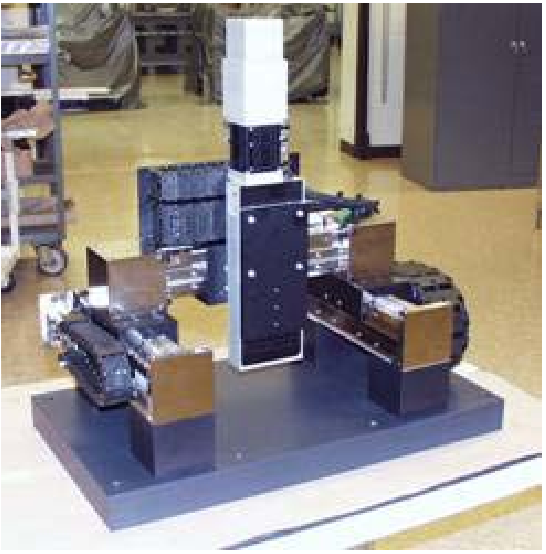
■ Hardware Components

■ Software Components

Suggested looks of Circuit Scan Family

CIRCUIT SCAN CS1000

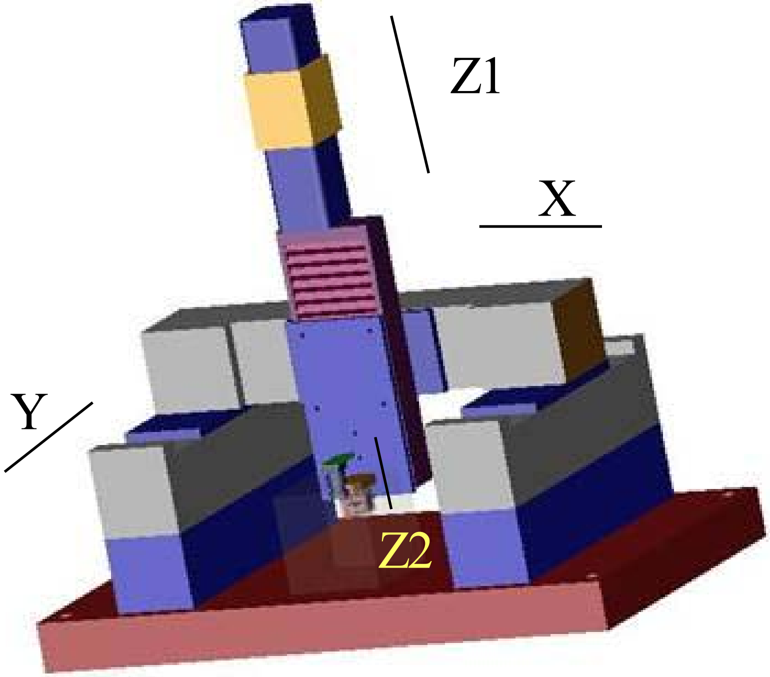
Machine Configuration



- Cartesian Machine with 4 AXIS

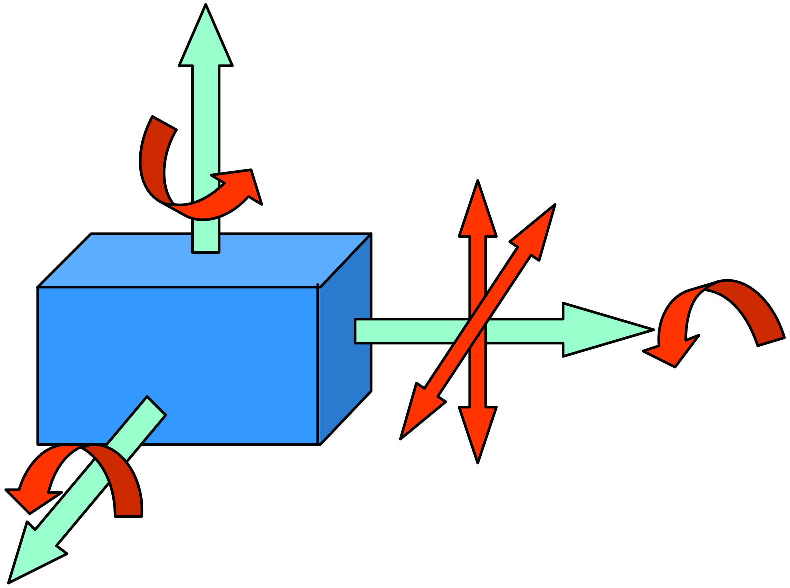
- Motion Details

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)

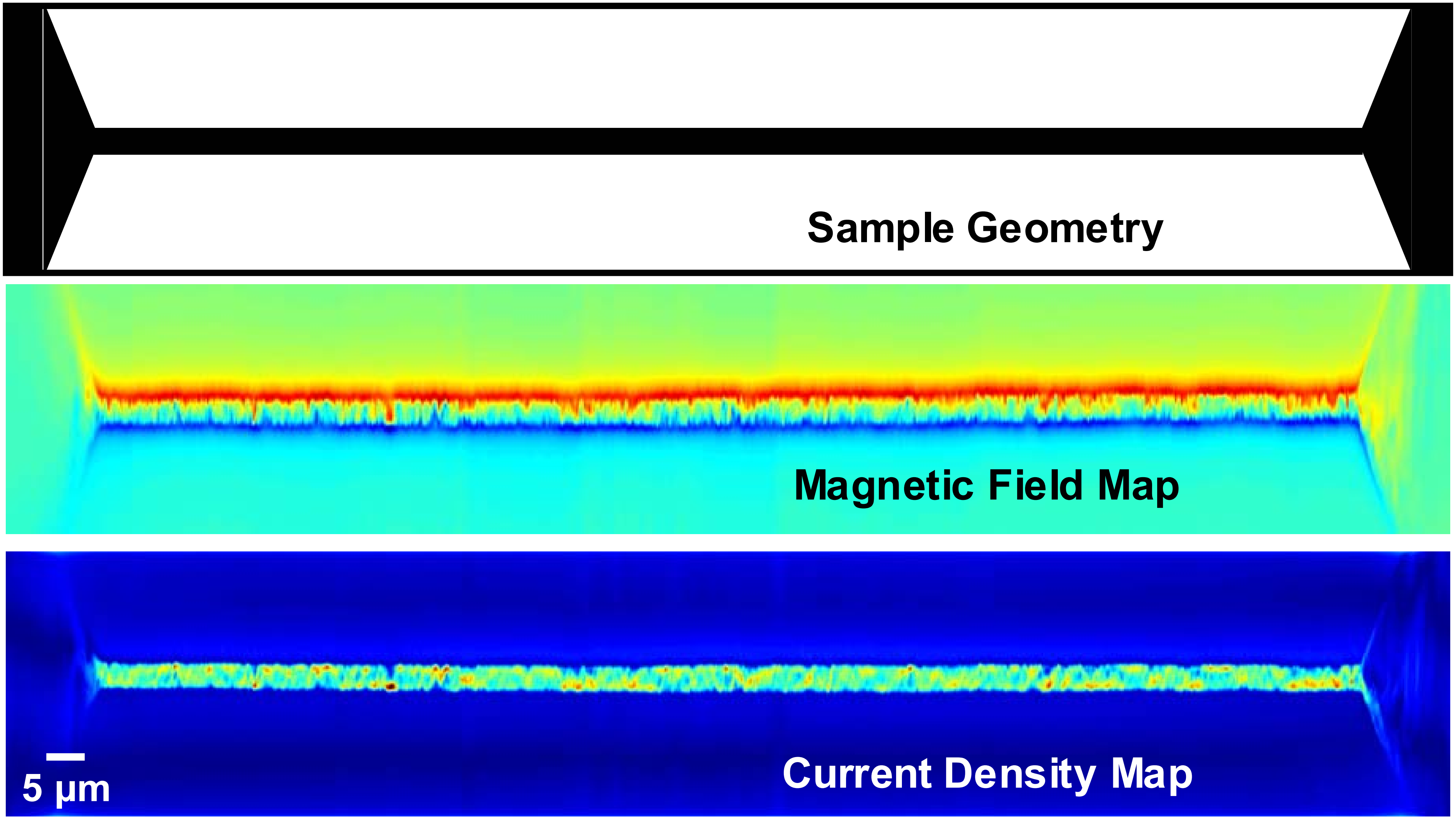
  Translational Scale Error – 1 Straightness –2

  Angular Roll, Pitch, Yaw – 3

  Squareness with other two axes – 2

Good News!! – For a determinitic machine these errors can be mesured and compensated.

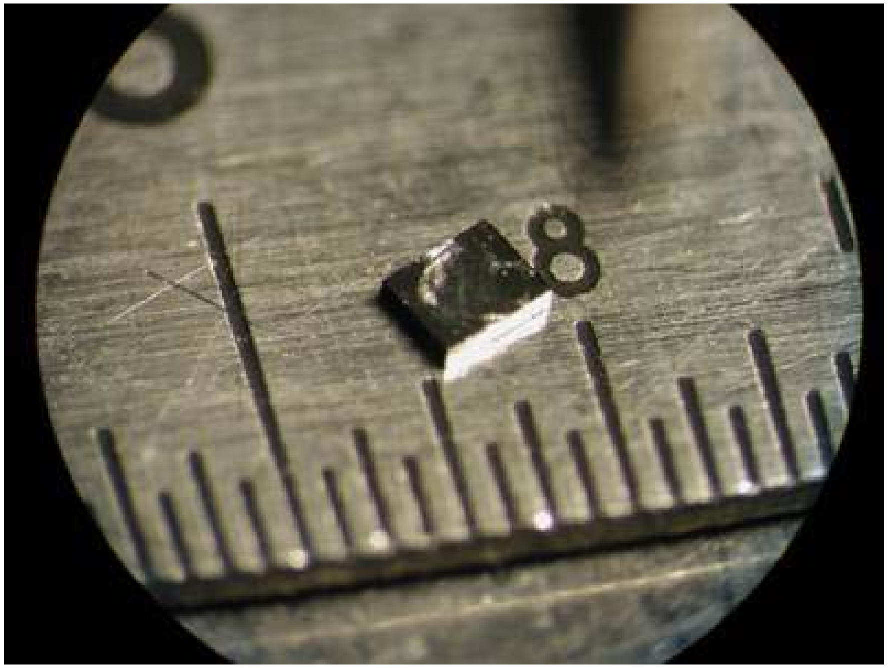
Sample Results



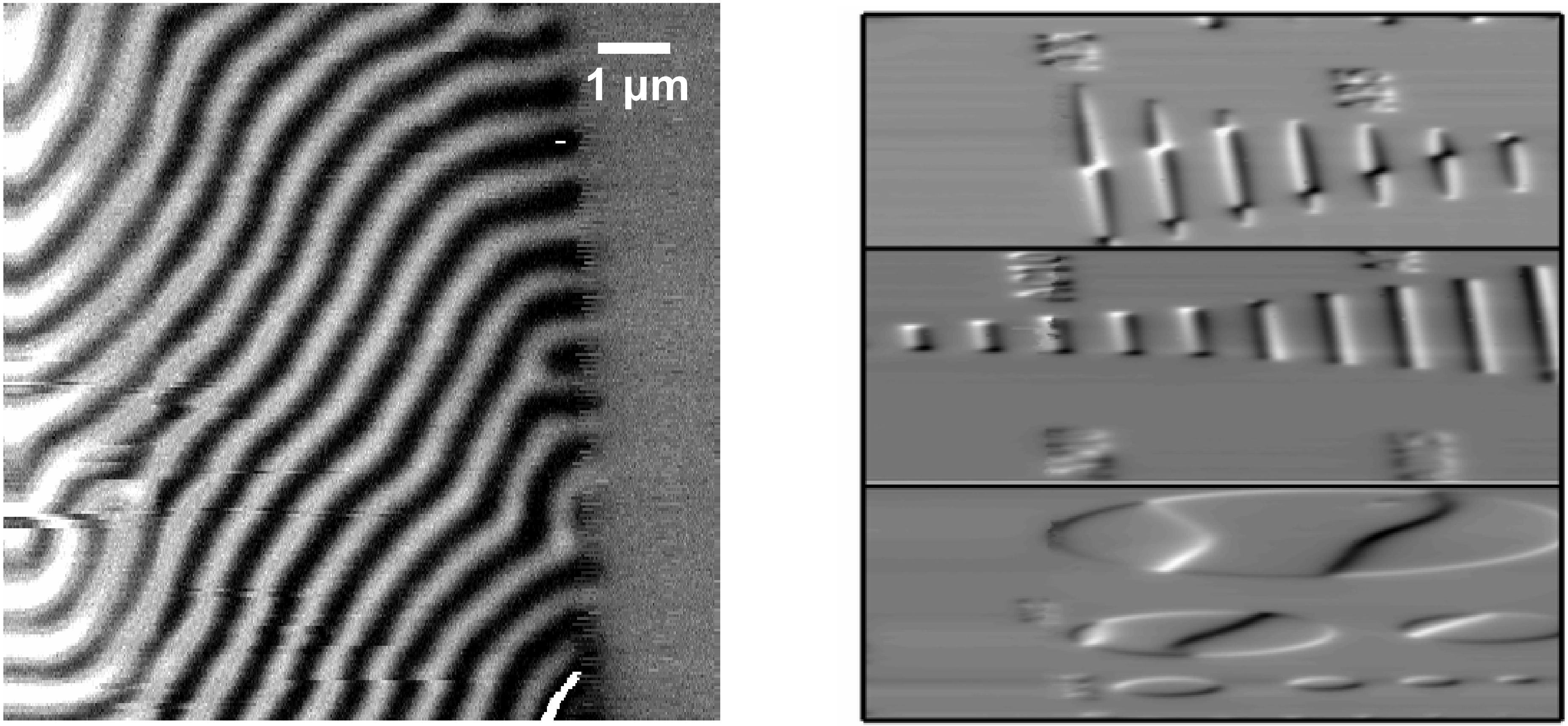
Notes on the technique

- 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

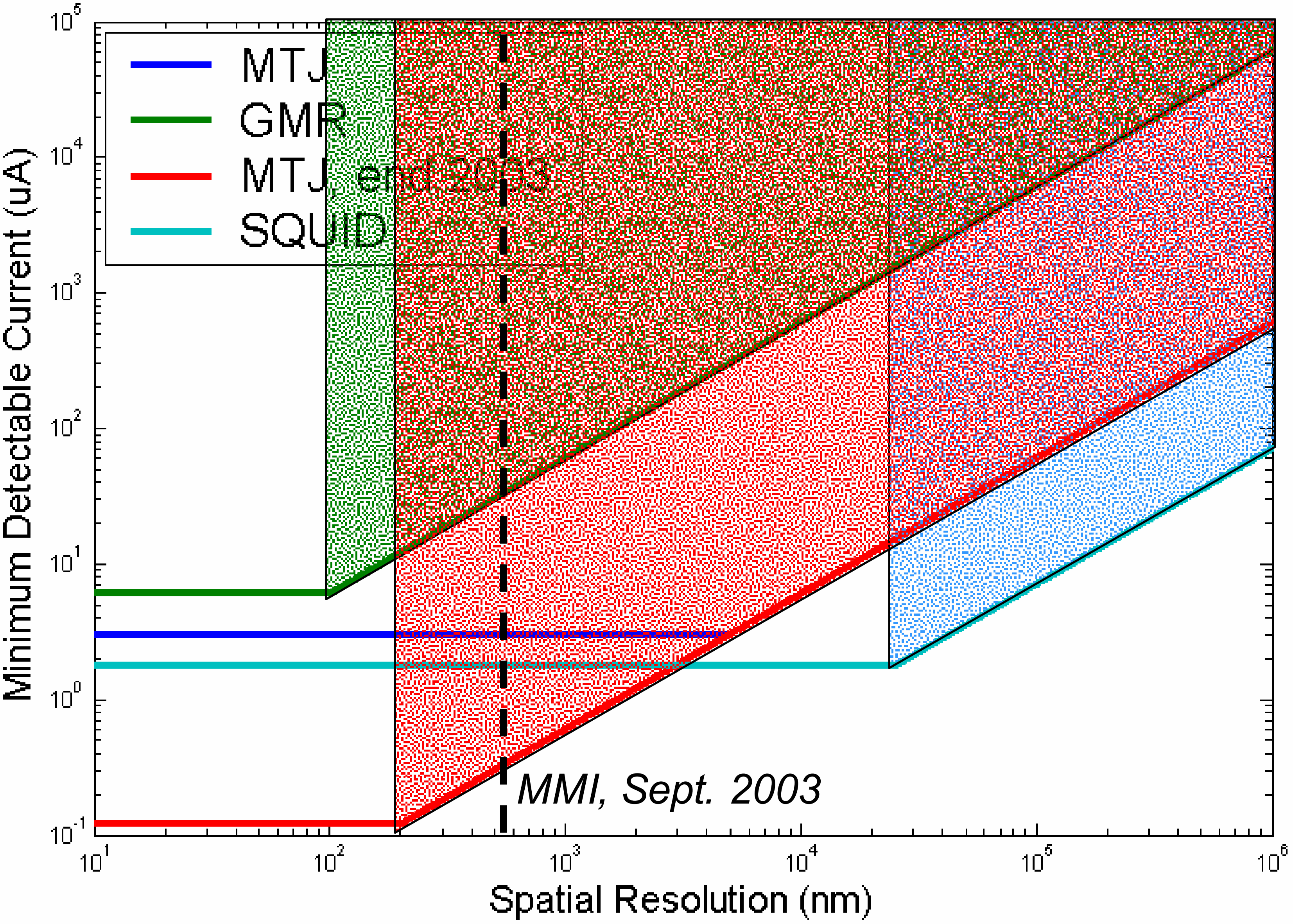


DC imaging: GMR (left) and MTJ (right)

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

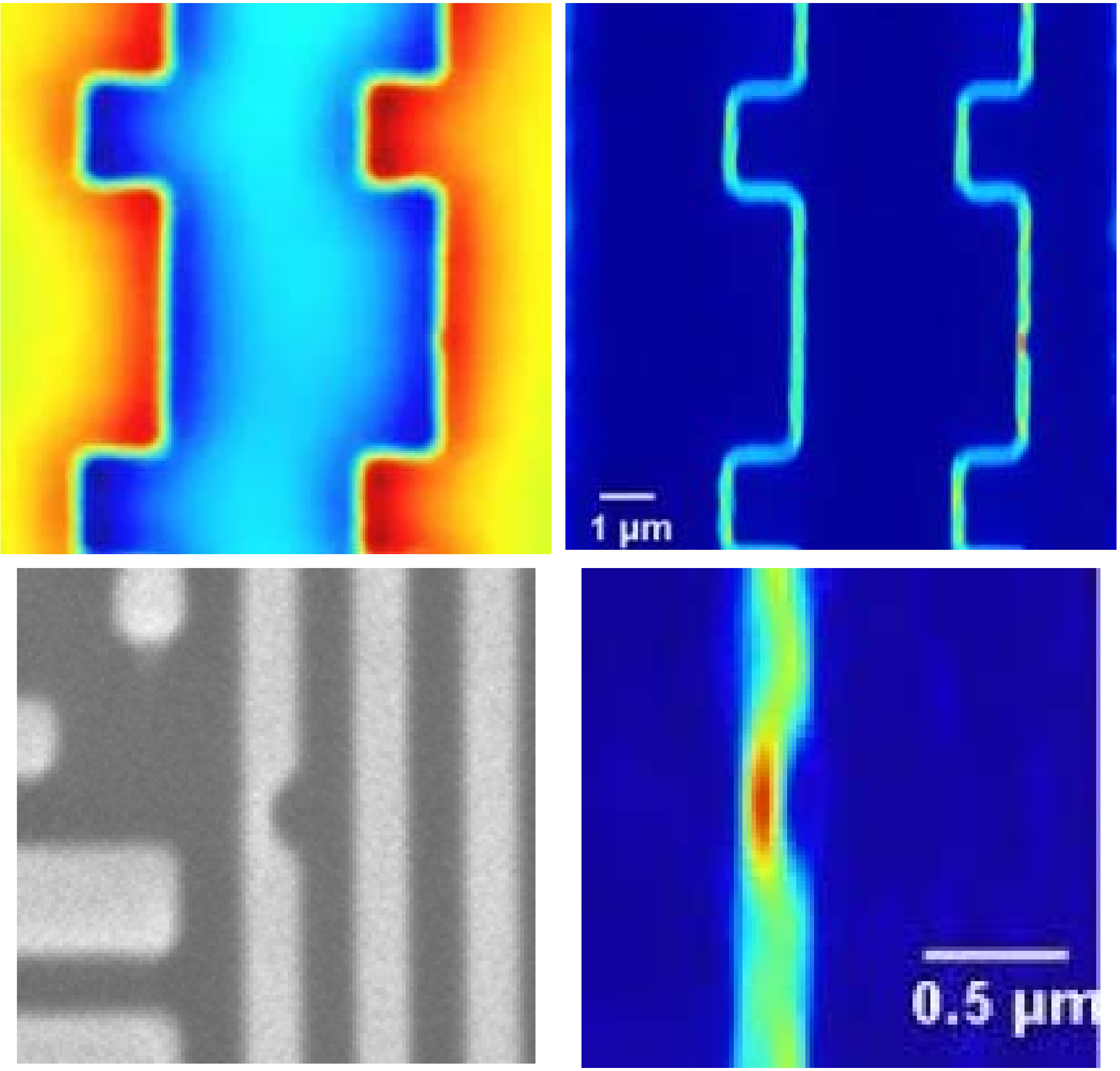
1 – Jury, et. al., IEEE Trans. Magn. **38** (5), 3545 (2002).
2 – MMI, unpublished.
3 – Liu, et. al., J. Appl. Phys. **92** (8), 4722 (2002).
4 – Chatraphorn et al., Appl. Phys. Lett. **76** (16), 2304 (2000).
5 – Kirtley, et. al., Annu. Rev. Mater. Sci. **29**, 117 (1999).
6 – MMI, unpublished. As of Sept. 2003, sensors capable of resolution of 500 nm have been demonstrated.


MTJ
GMR
MTJ, end 2003
SQUID
MMI, Sept. 2003
Minimum Detectable Current (uA)
Spatial Resolution (nm)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^1
10^2
10^3
10^4
10^5
10^6

Results 1: 125 nm edge defects

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

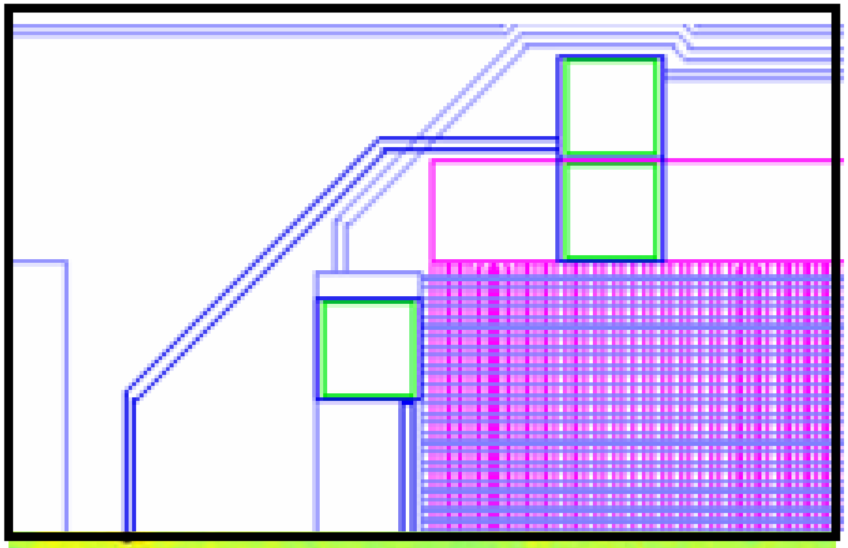
Current = 0.5 mA AC
Scan time = 5 minutes



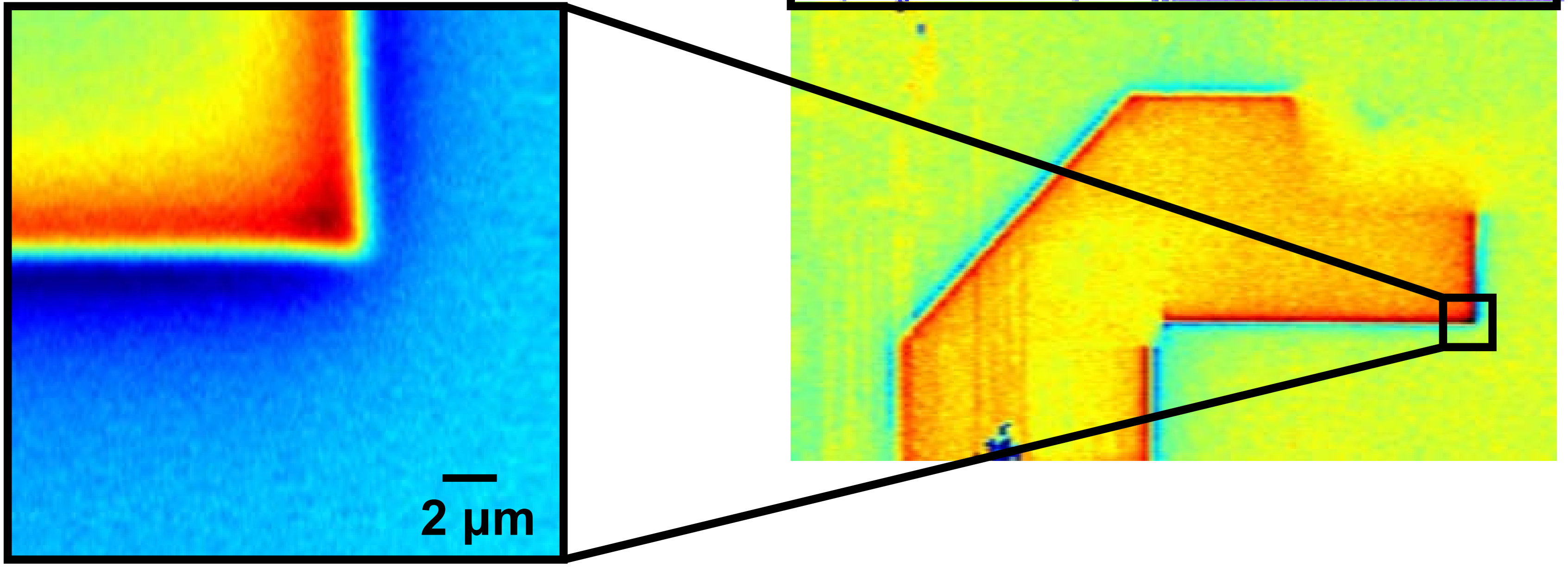
Results 2: Cross-point array failure

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.)

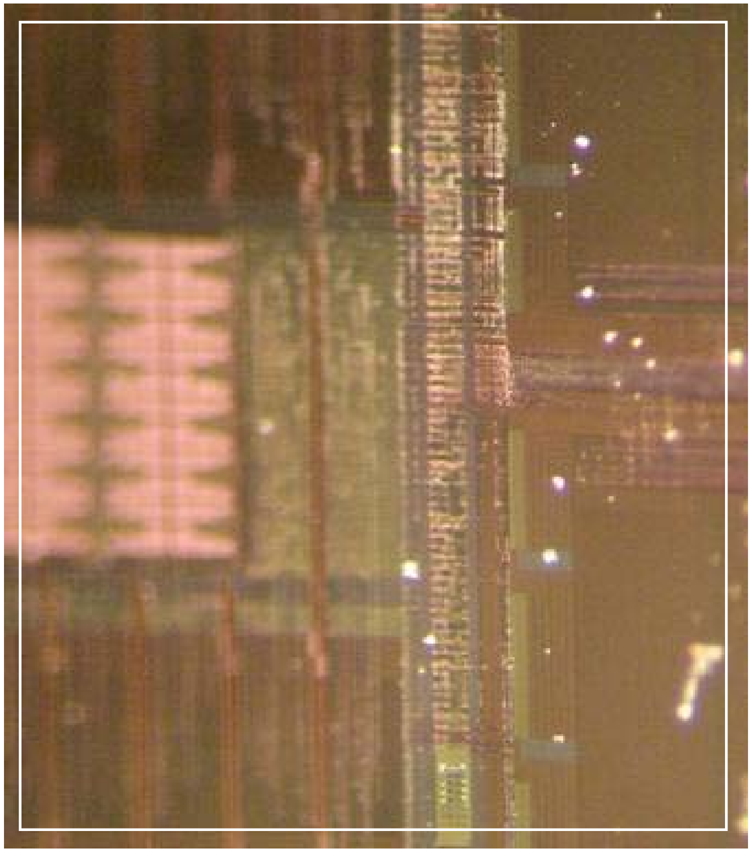


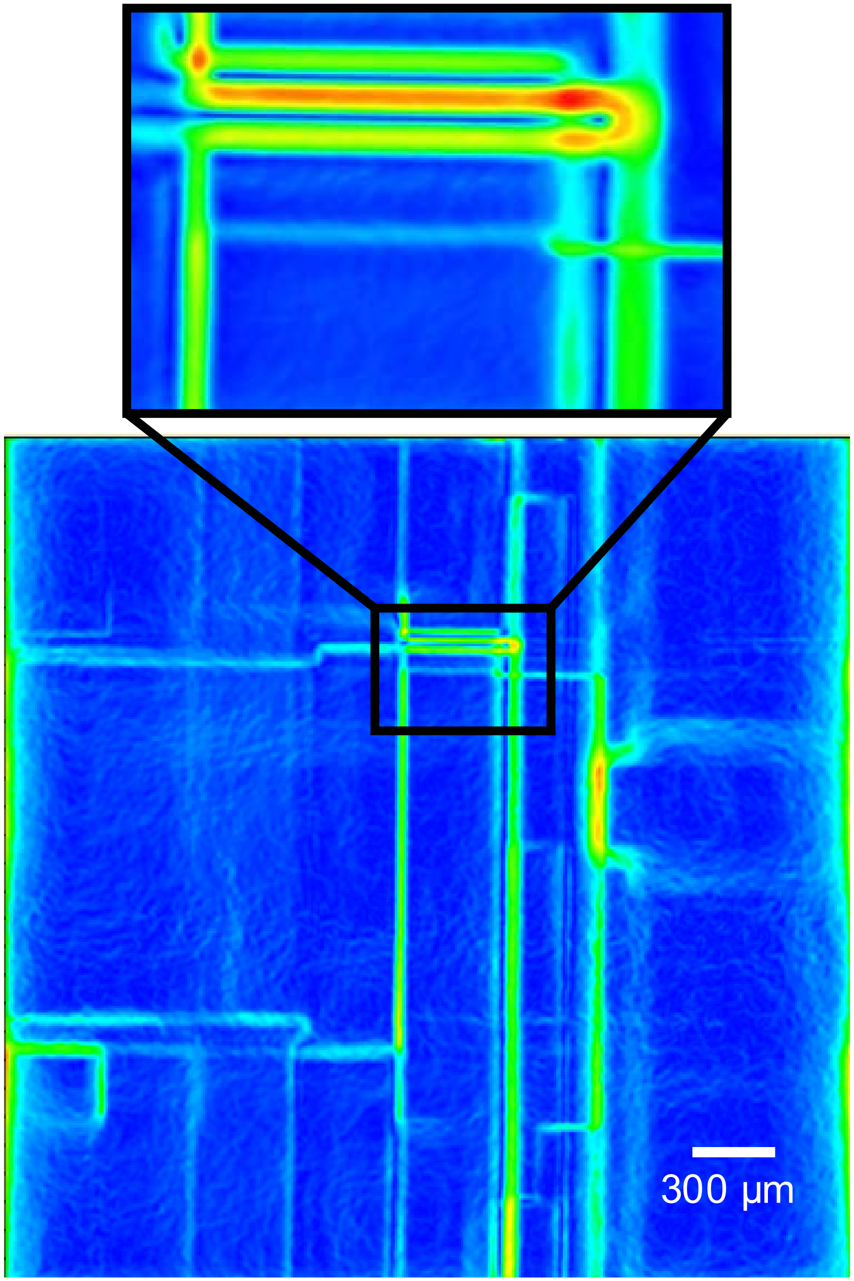
the “leaky pixel”



Results 3: Leaky logic chip

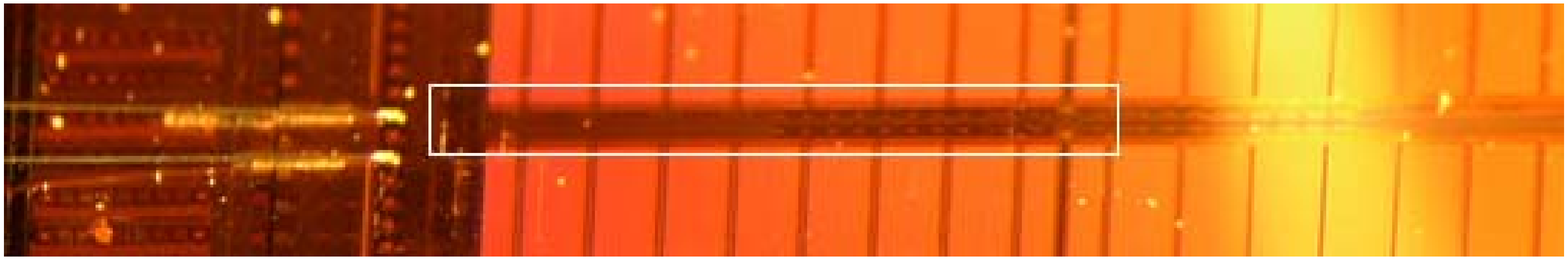
Operating logic chip powered at 1.4 V with 200 mV modulation signal.

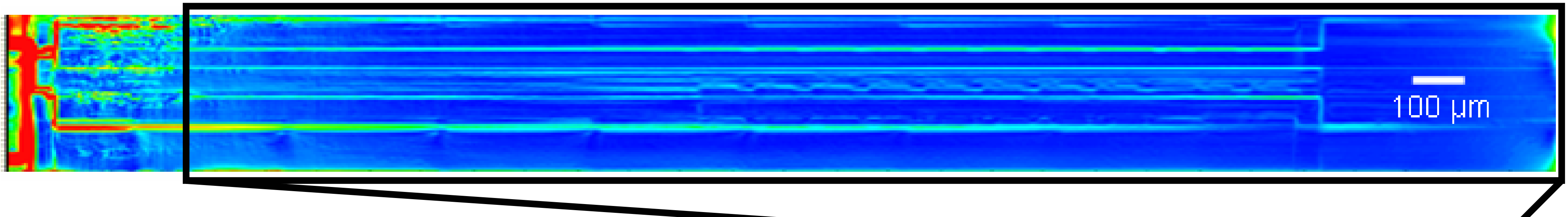




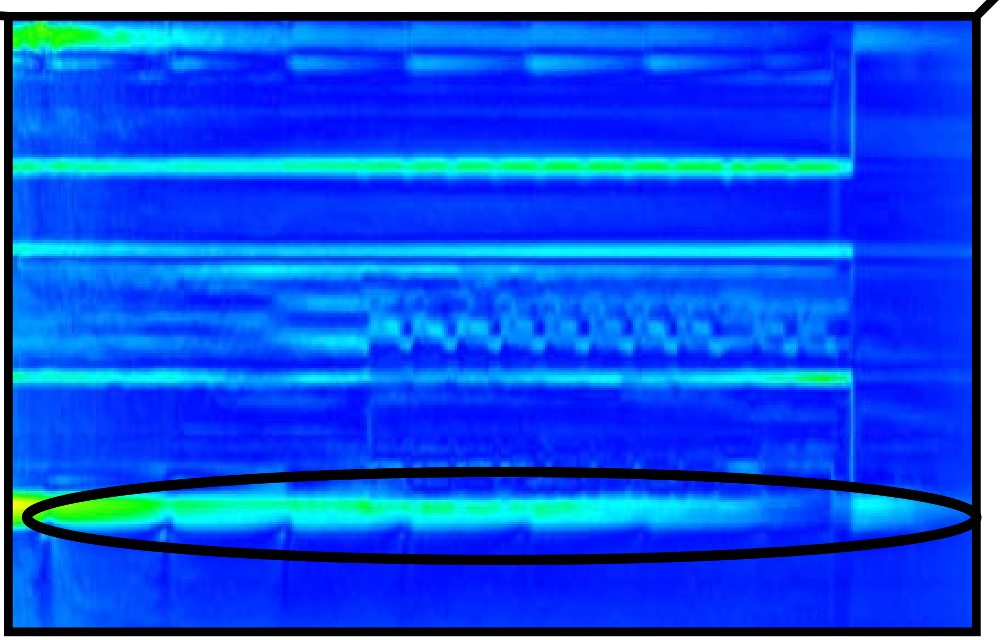
Results 4: Leaky SRAM device

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



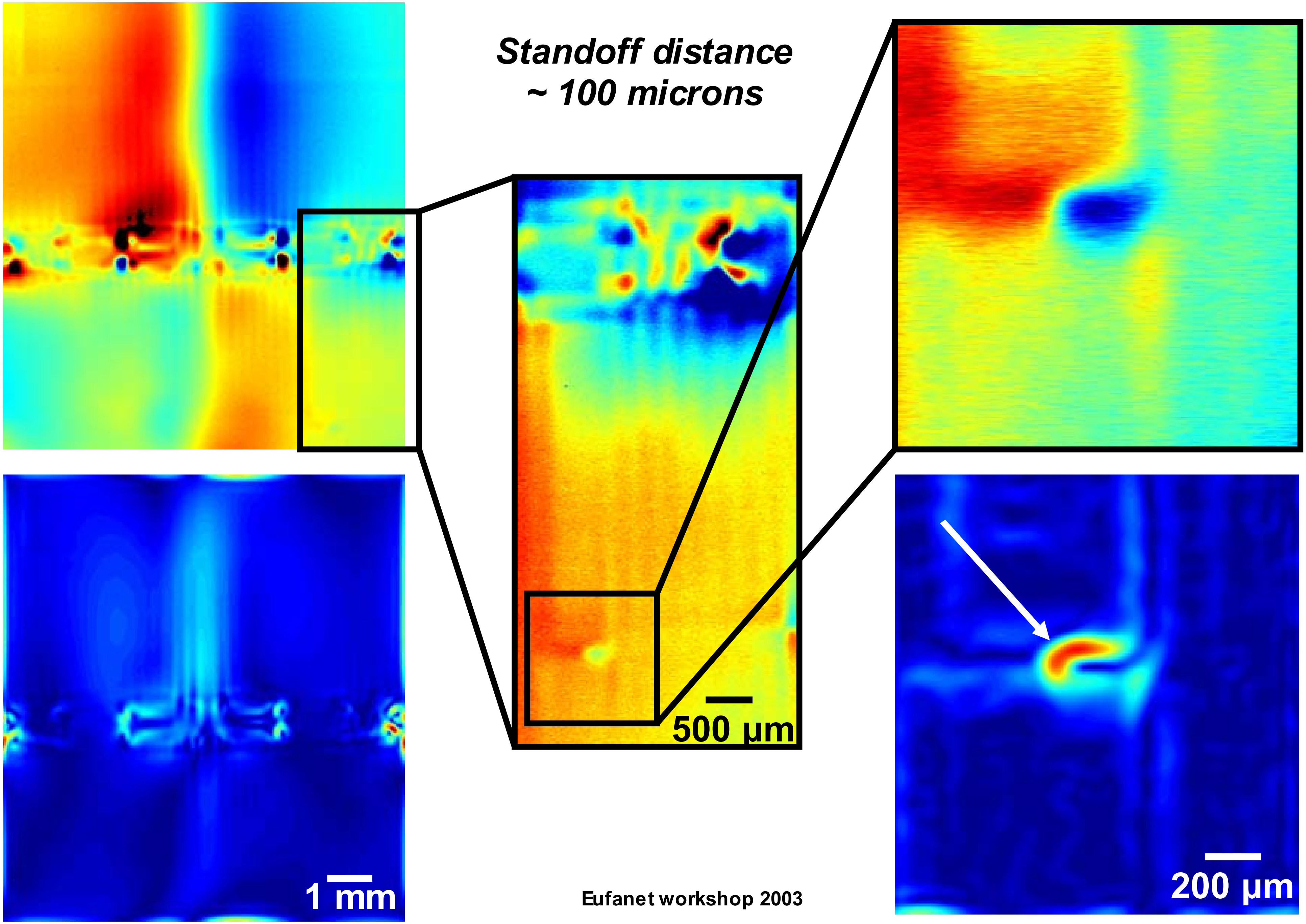


Above: Full scan at actual aspect.



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

Results 5: Flip-chip with FIB-induced short

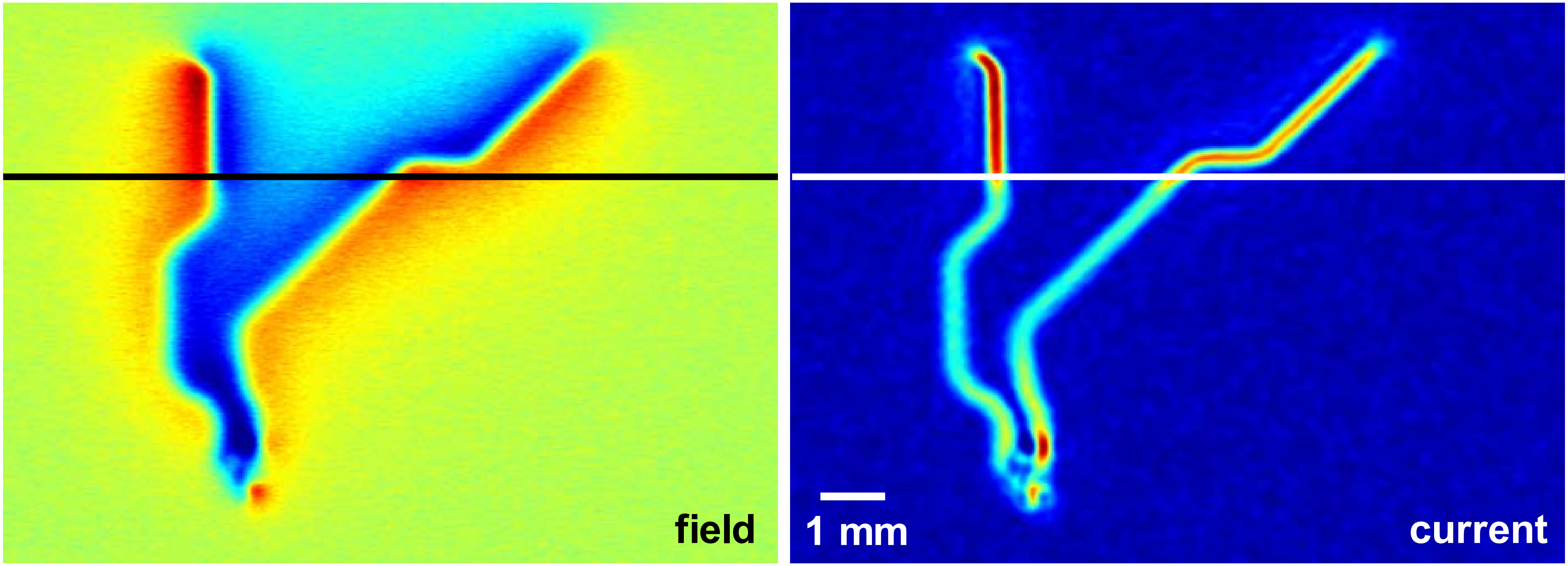


Standoff distance
~ 100 microns

Results 6: Current flow in a package

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

I = 0.7 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.