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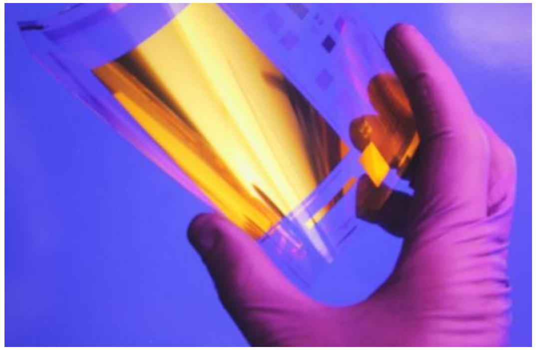
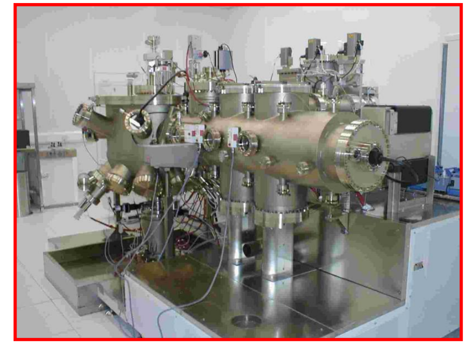
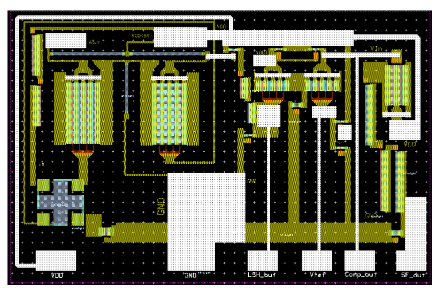


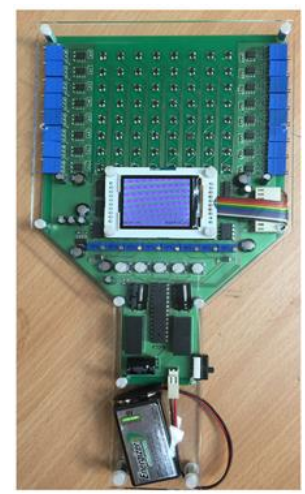


Quantum Well Hall Effect (QWHE) sensors and their applications

M. Missous, FREng

University of Manchester





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INTRODUCTION

Magnetic sensors are fundamental to engineering and the physical sciences and are indispensable components in many systems.

To date, virtually all magnetic sensors are either single elements or a small array of elements operated simultaneously (e.g. 3 component devices or small linear arrays). At best, present technology provides point, area average, or 1-Dimensional (assuming some form of linear translation) measurement of what is in reality a 4-D vector field (3-D space and time).

The ability to capture magnetic field data in more than one dimension would be of real value and would represent a major advance in the state of the art.

Two dimensional arrays of the type proposed here would allow direct high speed vision of magnetic fields, which could have an immediate impact on critical systems, especially those used for inspection or monitoring purposes.

Principle of Hall Effect Sensing

- When a conductor carrying a current (I) is placed in a magnetic field (B) and oriented so that the current and magnetic field are at right angles, an electric field is produced in the conductor at right angles to both current and magnetic field and produce a Hall Voltage (V_h) given by:

$$\mathbf{V_h = K_h \cdot B \cdot I}$$

$$K_h = \frac{1}{t.n.e}$$

Where the sensitivity K_h is given by:

t: Thickness

n: Electron concentration

e: Electron charge

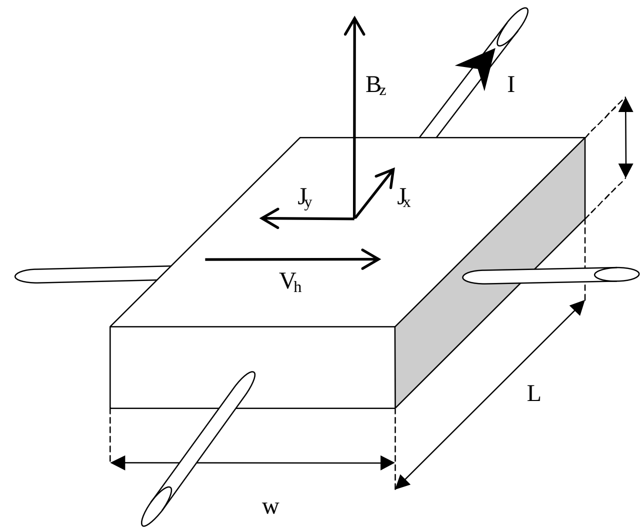


Fig. 1. Hall effect phenomenon

Quantum Well Hall Effect sensors

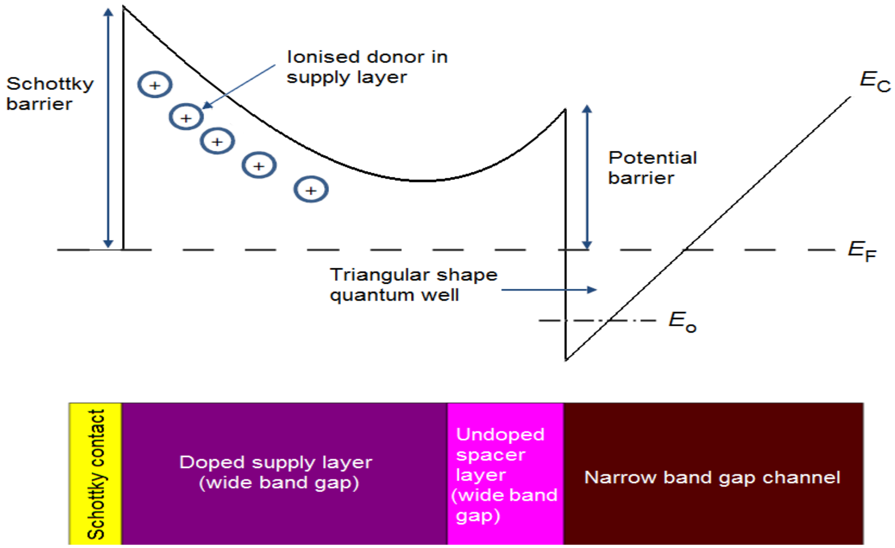
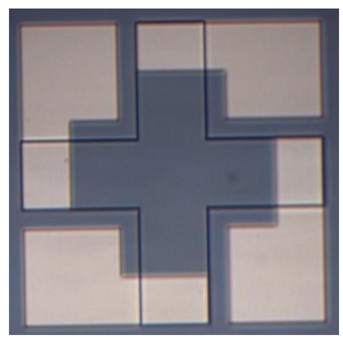


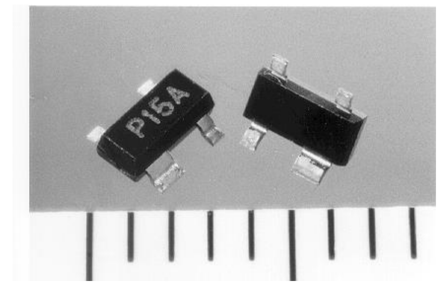
Fig.2 Formation of 2DEG Quantum Well at AlGaAs/InGaAs heterojunction

GaAs	Cap layer
$Al_xGa_{(1-x)}As$	Supply layer
$Al_xGa_{(1-x)}As$	Spacer layer
$In_{0.15}Ga_{0.85}As$	Quantum Well
GaAs	Buffer layer

← Silicon δ layer



2 µm to 70 µm



2 mm

packaged sensor

GaAs-InGaAs-AlGaAs QWHE structure and Greek cross geometry with length to width ratio of 3.

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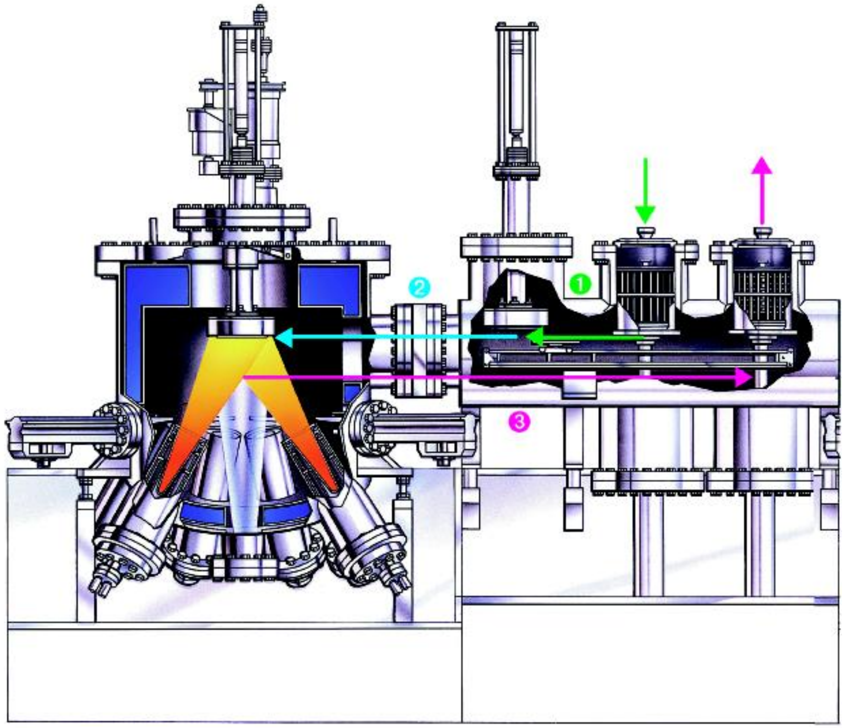
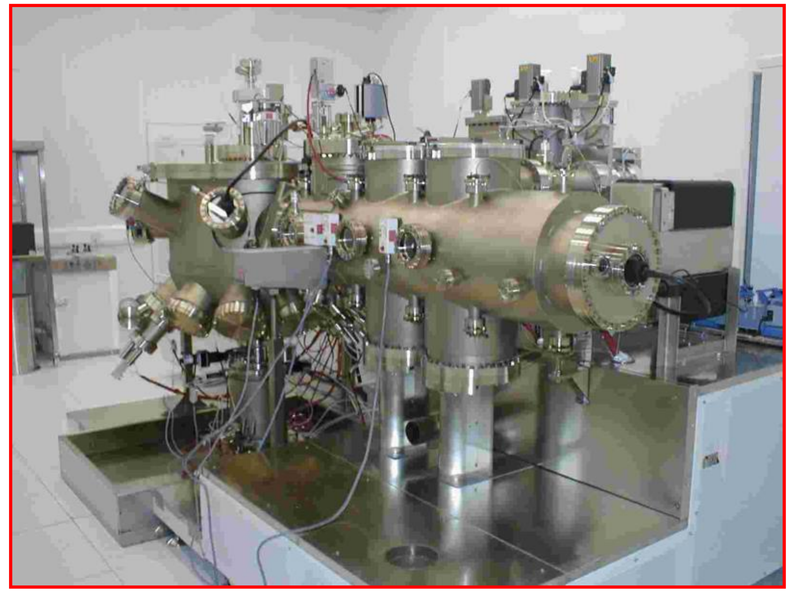
SEMICONDUCTOR THIN FILM SYNTHESIS :MOLECULAR BEAM EPITAXY (MBE)



MBE is the ultra high vacuum evaporation of a single crystal oriented overgrowth, from independently controlled constituent species.



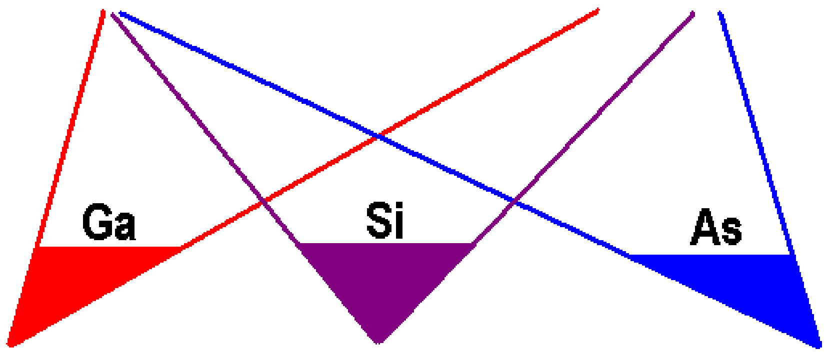
RELIES ON UHV TECHNOLOGY

- Ultra clean UHV (pp. O_2, H_2O, CO, CO_2 << 1 x 10^{-12} Torr)

EPITAXY

GaAs SUBSTRATE : 500 µm

MBE LAYER : 1 µm



Ga + As → 10^{22} atoms cm^{-3}

Si (<u>or</u> Be) → 10^{16} atoms cm^{-3}

YIELD :

~ 40,000 Hall Sensor die per 4" wafer :

"All identical"

Purity	:	Better than parts per million
Uniformity	:	< 1%
Precision	:	< One atomic layer
Time for Deposition	:	~ 1 hour

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Hall Effect Devices Parameters/Limitations

- Offset Voltage:
  - Piezoresistance Effect
  - Misalignment.
- Noise
  - 1/f Noise
  - Thermal noise
- Self Induced Magnetic Field
  (due to passage of applied current)
- Frequency Limitation
  Restricted by relaxation time of
  the dielectric material >> GHz

- Sensitivity
  - Current sensitivity S_i

$$S_i = \frac{V_h}{IB}$$

  - Voltage sensitivity S_v

$$S_v = \mu_h \frac{W}{L} G$$

- Linearity
- Effect of Temperature
  - Joule Heating
  - Ambient temperature

Magnetic Field Sensors Spectrum

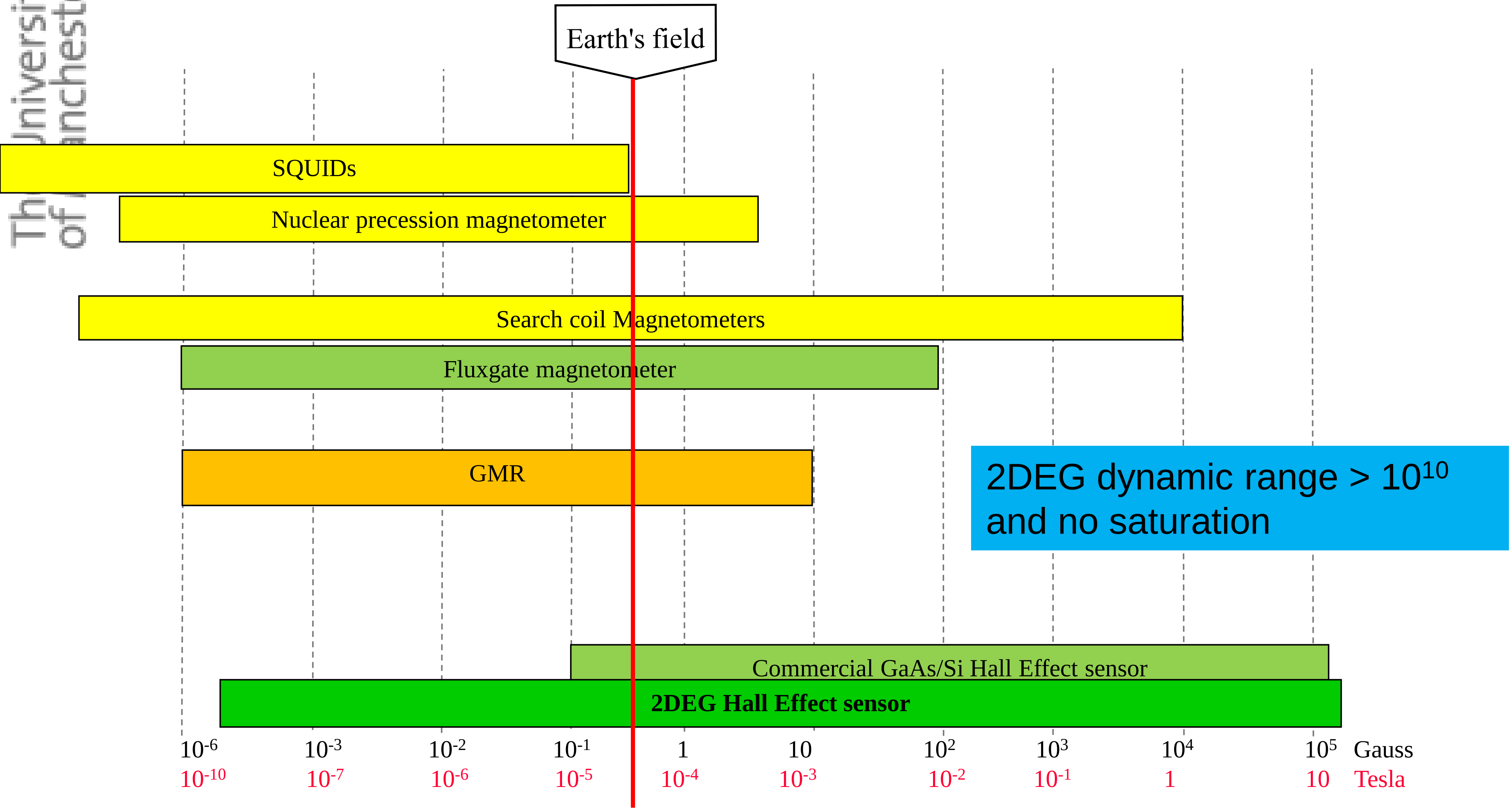


Fig.3. Magnetic field sensor spectrum

Solid State Magnetic Sensors : Field sensors and Flux sensors.

The most sensitive magnetic sensors are Flux sensors but at the expense of size

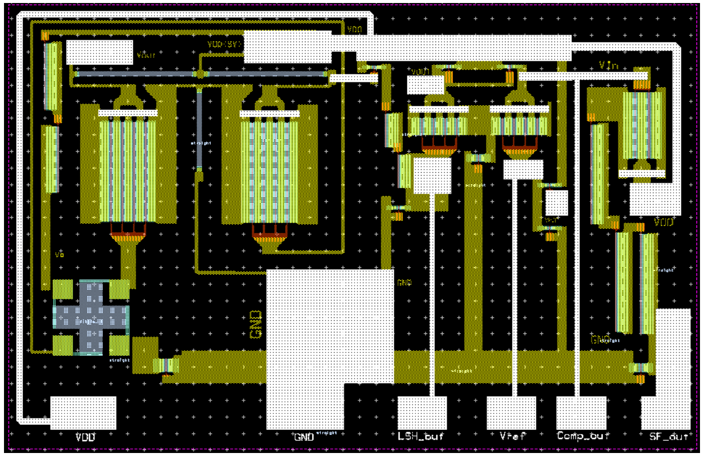
(Magnetic induction)

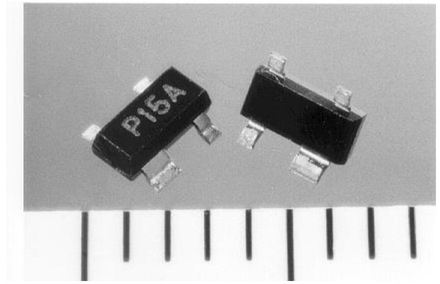
Field sensors measure flux density rather than flux and thus sensitivity is independent of size.

(Hall Effect, AMR and GMR)

Field sensors have an inherent advantage in size and power when compared to search coils ,flux gates, and more sophisticated sensing techniques such as Superconducting Quantum Interference Detectors (SQUID).

The sensing can be done in an extremely small, lithographically defined area increasing the resolution for fields that change over small distances and allows for packaging arrays of sensors in a small footprint.





As Hall effect devices are field sensors, their response does not depend on size, and thus micron sized elements can be fabricated.

Due to their small size, these sensors can also be used to field mapping purpose, where a single sensor integrating several elements can be used.

Furthermore the QWHE devices can also be fabricated into transistors therefore enabling integrated circuit configurations with nT/√Hz sensitivity (unlike GMR or AMR).

Unlike Si integrated Hall sensors, the QWHE are radiation resistant and capable of operating in harsh environments (~ 200 °C)

Noise sources in a QWHE Sensor

The noise in a typical semiconductor devices is given by :

$$S_{V,\mathrm{noise}} = \alpha\, G_n \frac{E^2}{f\, n_{2-D}} + 4\, k_B\, T\, R + \sum_i A_{i,g-r} \frac{1}{1 + (2\pi f \tau_i)^2}$$

α is the Hooge parameter, E is the external electric field applied to the device, G_n is a geometrical correction factor, f is operating frequency, n_{2-D} is the 2-D electron concentration, $A_{i,g-r}$ is the amplitude of g−r noise, τ_i is a characteristic time constant of the generation-recombination process, k_B is Boltzmann constant, T is ambient measurement temperature and R the sample resistance.

Noise sources at high frequencies

Johnson or resistance noise, dominant above 1 to 10kHz,

$V_n = (4kTBR)^{1/2}$, in units of volts/(Sq-root Hz.)

k is Boltzman's constant, $k = 1.38 \times 10^{-23}$ Joule/Kelvin.

B = Bandwidth in Hz.

R = Resistance in Ohms.

T = Temperature in degrees, K. (deg.K = deg.C + 273)

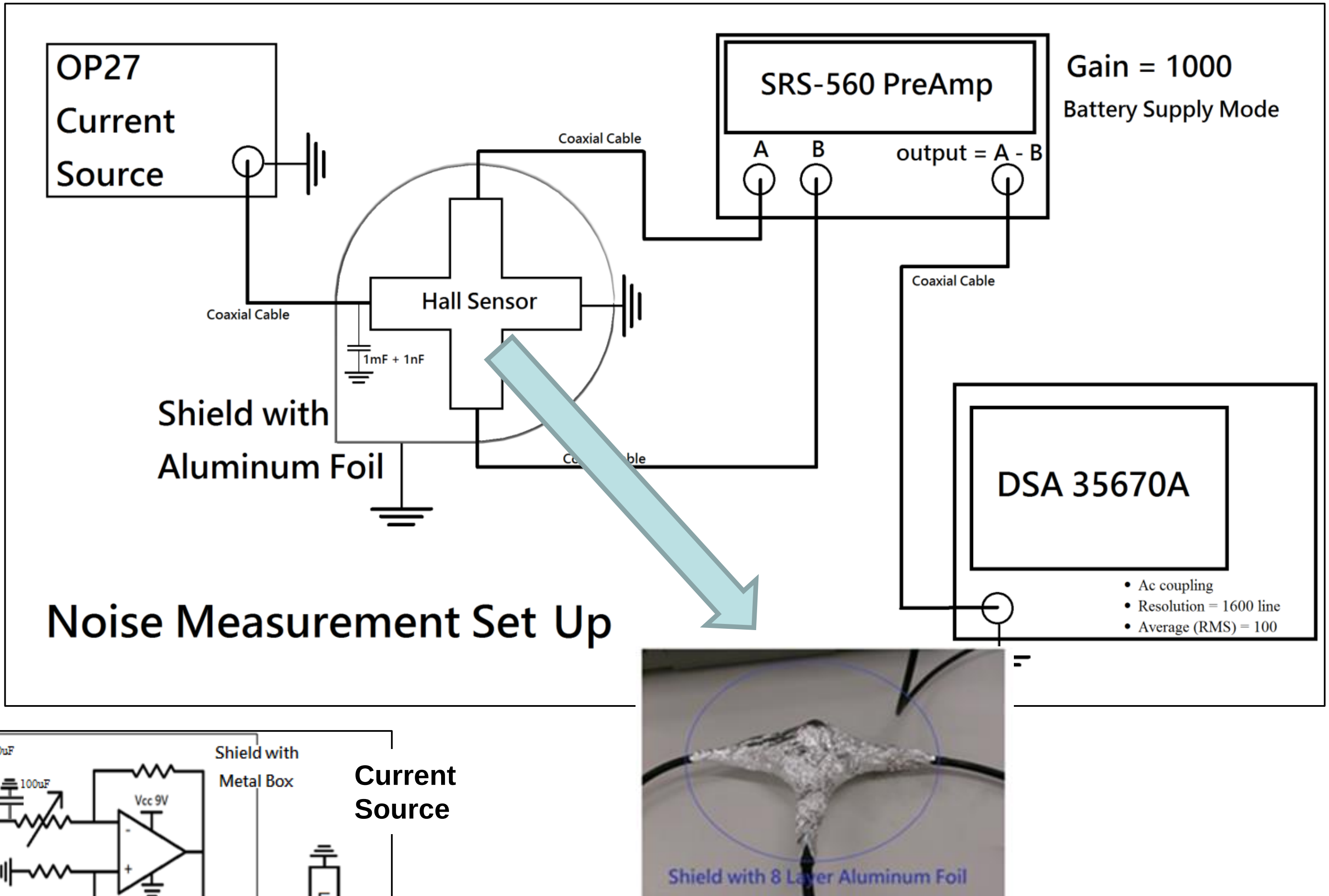
The minimum B-field occurs when the S/N ratio is equal to 1

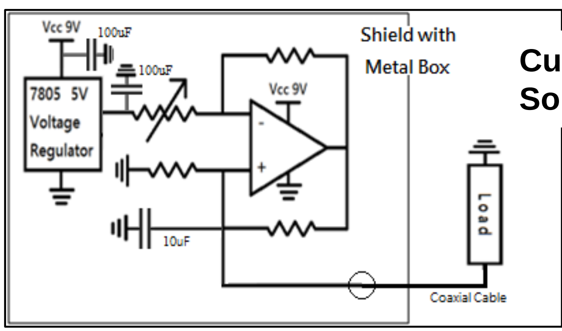
ie

$$\frac{S}{N} = \frac{I_B k G B_{min}}{\sqrt{4kTR}}$$ and hence $$B_{min} = \frac{\sqrt{4kTR}}{I_B k G}$$

k is Hall sensitivity and G is magnetic gain (do not confuse with geometrical factor!).

NOISE MEASUREMENTS

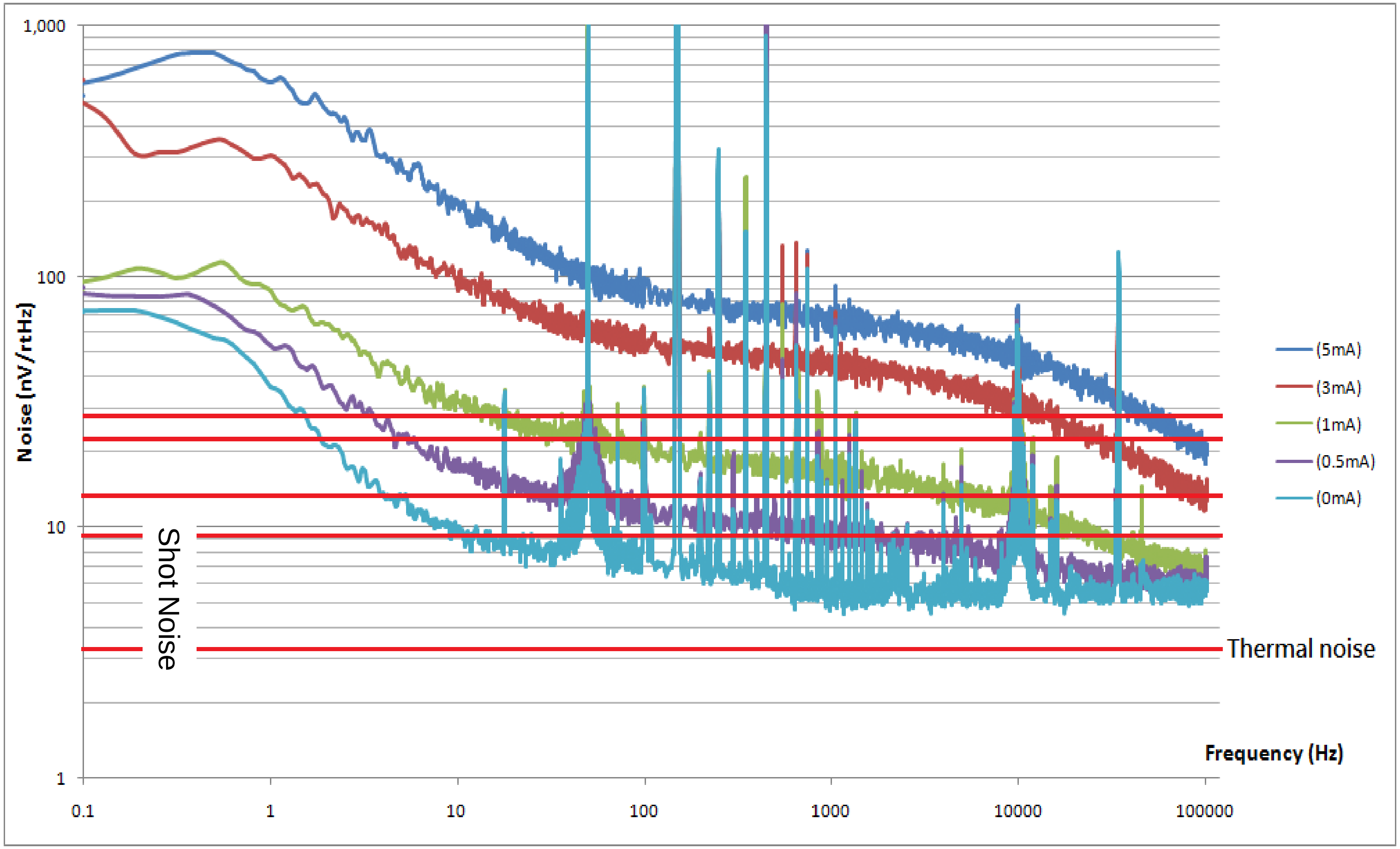




Current Source

Fig. 4 Noise Measurements

NOISE CHARACTERISTICS



PreAmp : SRS560   DSA : Agilent35670A   Current Source : OP27

Fig. 5 Noise characteristics (P2A)

B_{min} CHARACTERISTICS

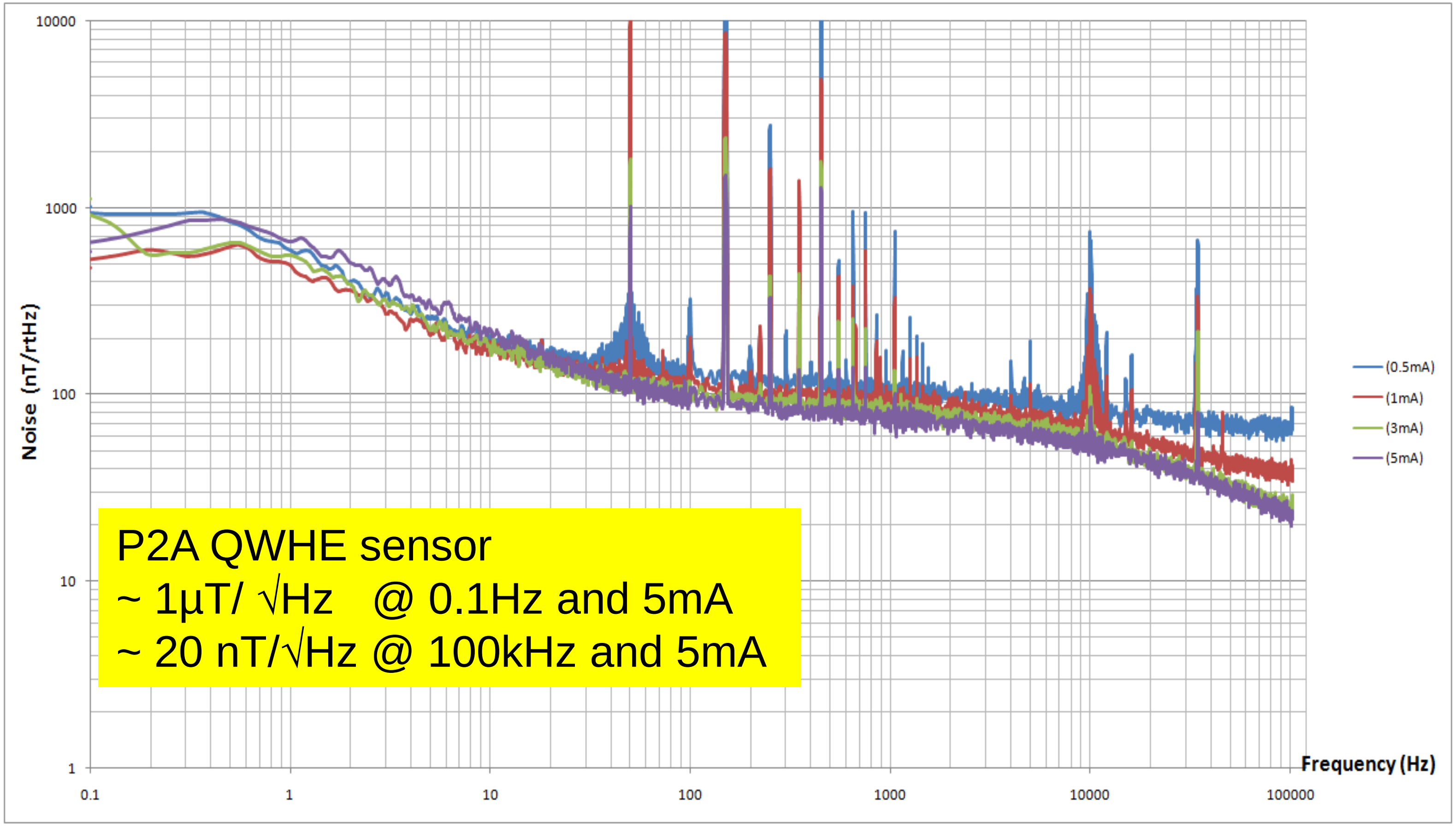
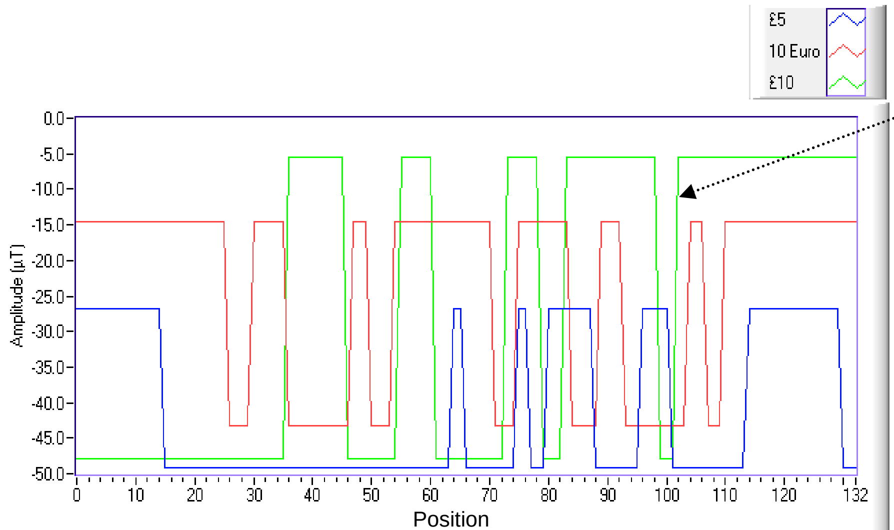


Fig. 6 Minimum B-Field detection as a function of frequency

Single Sensor applications

1D Passive Magnetic Imaging : Bank Notes Scanning

- Using a scanning DC magnetic field mapping system, a £5 and £10 UK and €10 Euro bank notes were scanned.



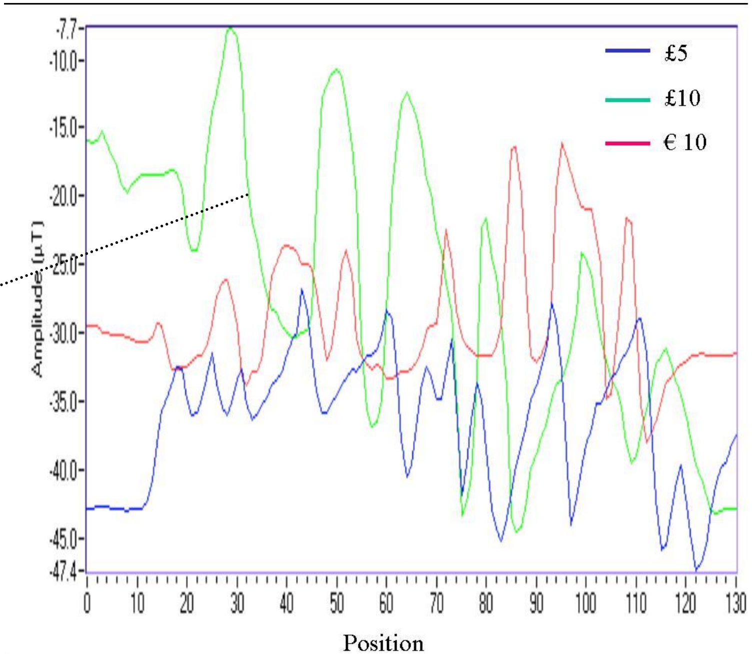
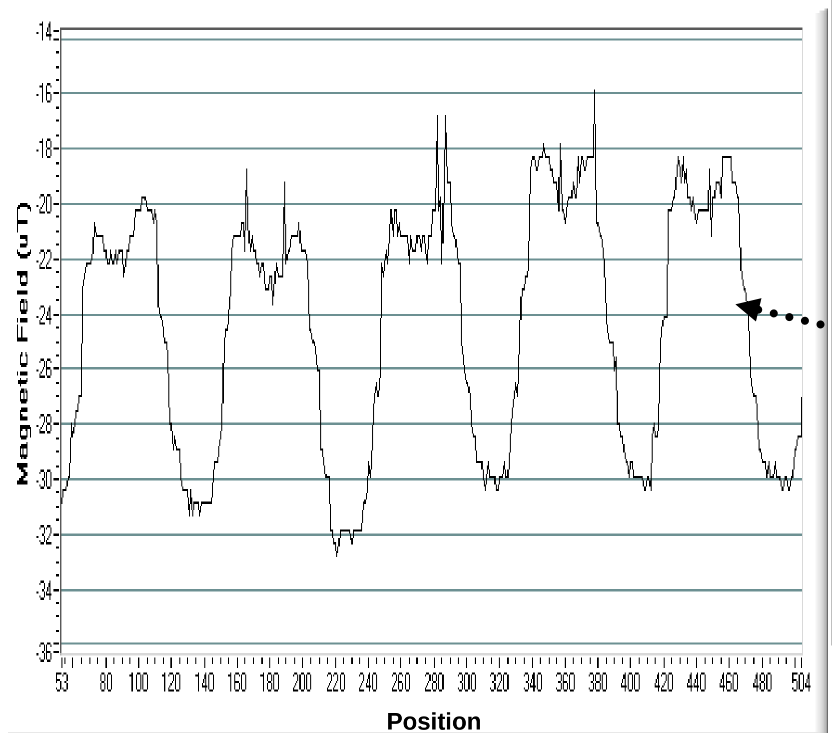


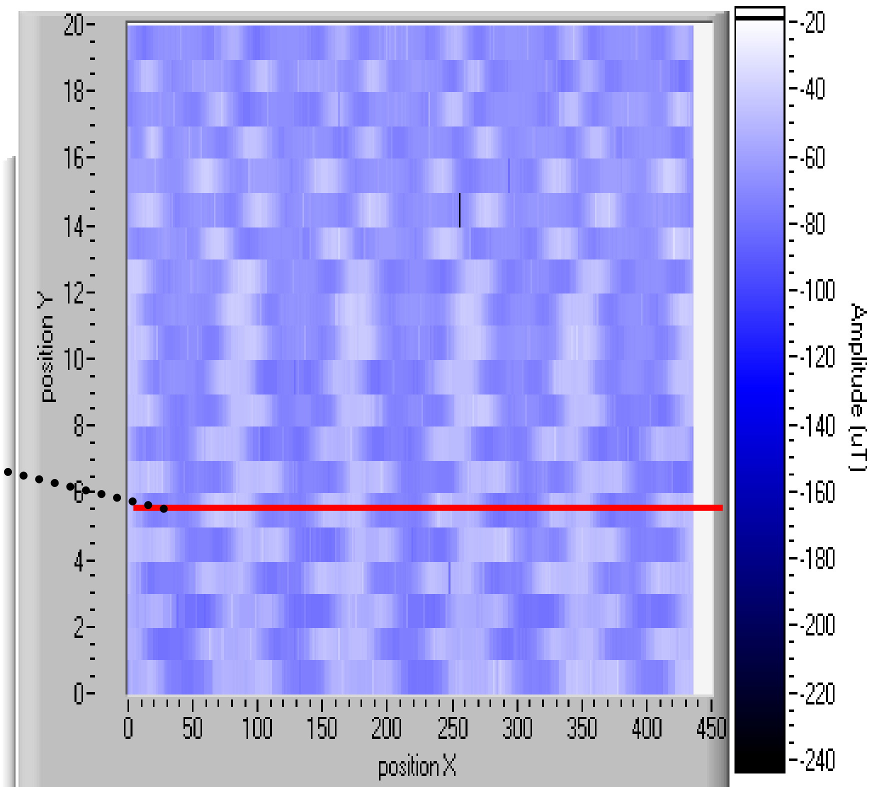
Figure 7. Processing of scanned bank notes raw signals

Scanning of £5, £10 UK and €10 bank notes
over metal strip , magnetic field strength ~ 5µT

2D passive magnetic imaging

- Magnetic disk scan of an 5 x 5 mm^2 area, the tracks of the disk are displayed as vertical lines.





Floppy disk scanning

Figure 8. Cross section of red line , magnetic flux density variations ~ 10 µT

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COMPARISONS WITH GMR and AMR

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AMR and GMR sensors

JOURNAL OF APPLIED PHYSICS **97**, 10Q107 (2005)

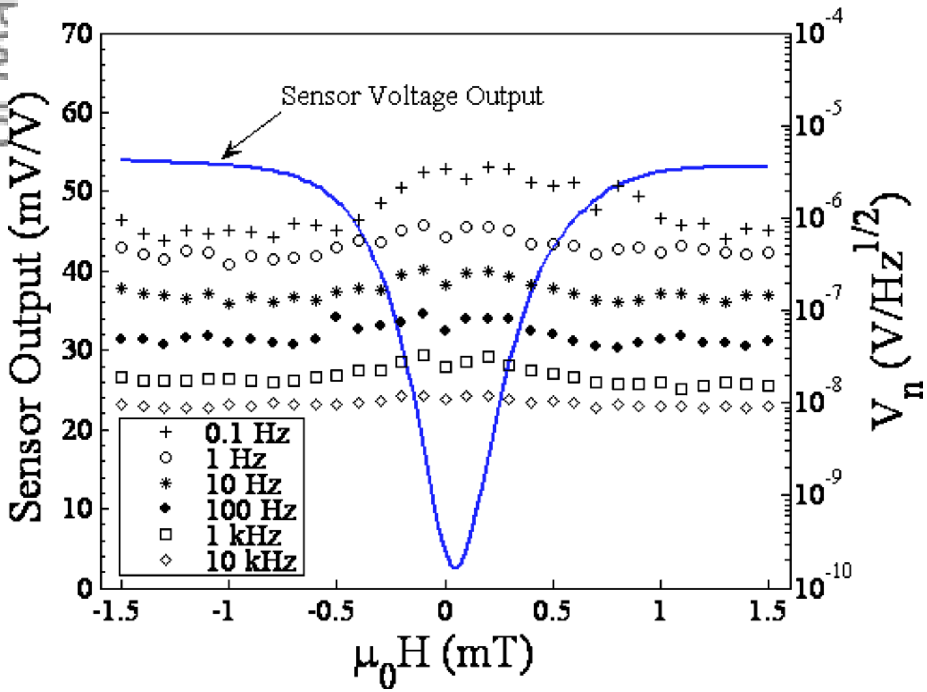
Low-frequency noise measurements on commercial magnetoresistive magnetic field sensors

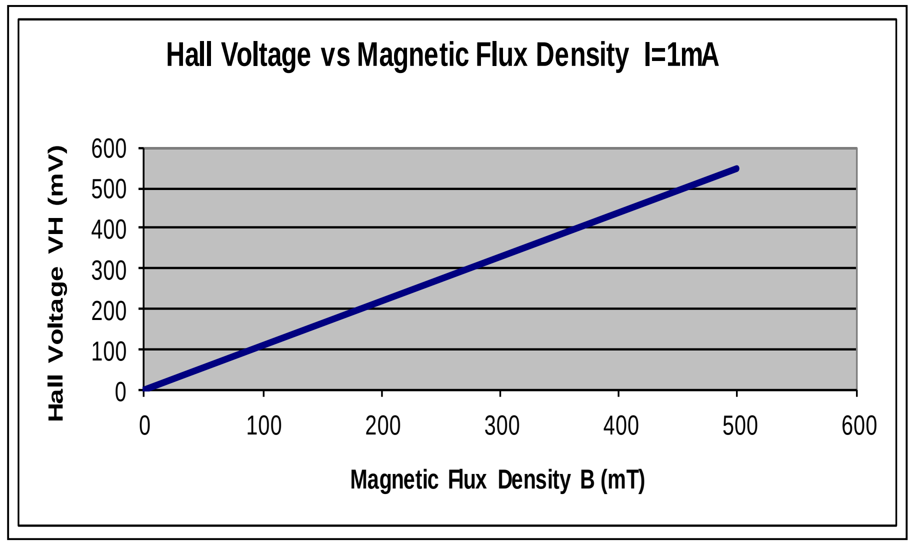
Nathan A. Stutzke,[a] Stephen E. Russek, and David P. Pappas
Electromagnetics-Magnetics Group, National Institute of Standards and Technology, 325 Broadway-MC 818.03 Boulder, Colorado 80305

Mark Tondra
Nonvolatile Electronics (NVE) Corporation, 11409 Valley View Road, Eden Prairie, Minnesota 55344-3617

(Presented on 8 November 2004; published online 17 May 2005)

AMR and GMR sensors





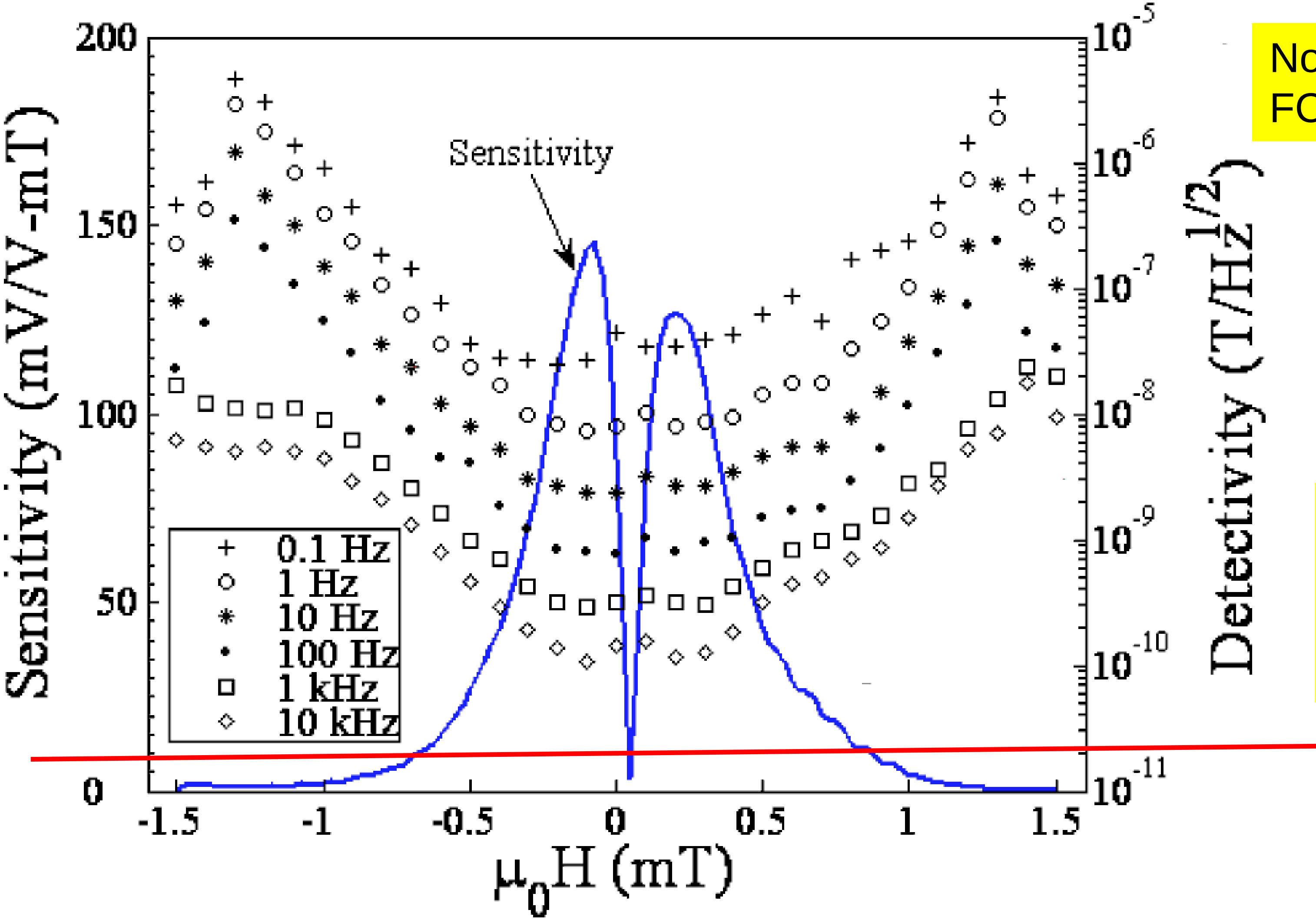
Die Size: 1.65 x 2.14 mm

Die Size: 0.3 x 0.3 mm
40 times smaller than GMR

Maximum operating Temp ~125 C

Maximum operating Temp ~200 °C

AMR and GMR sensors

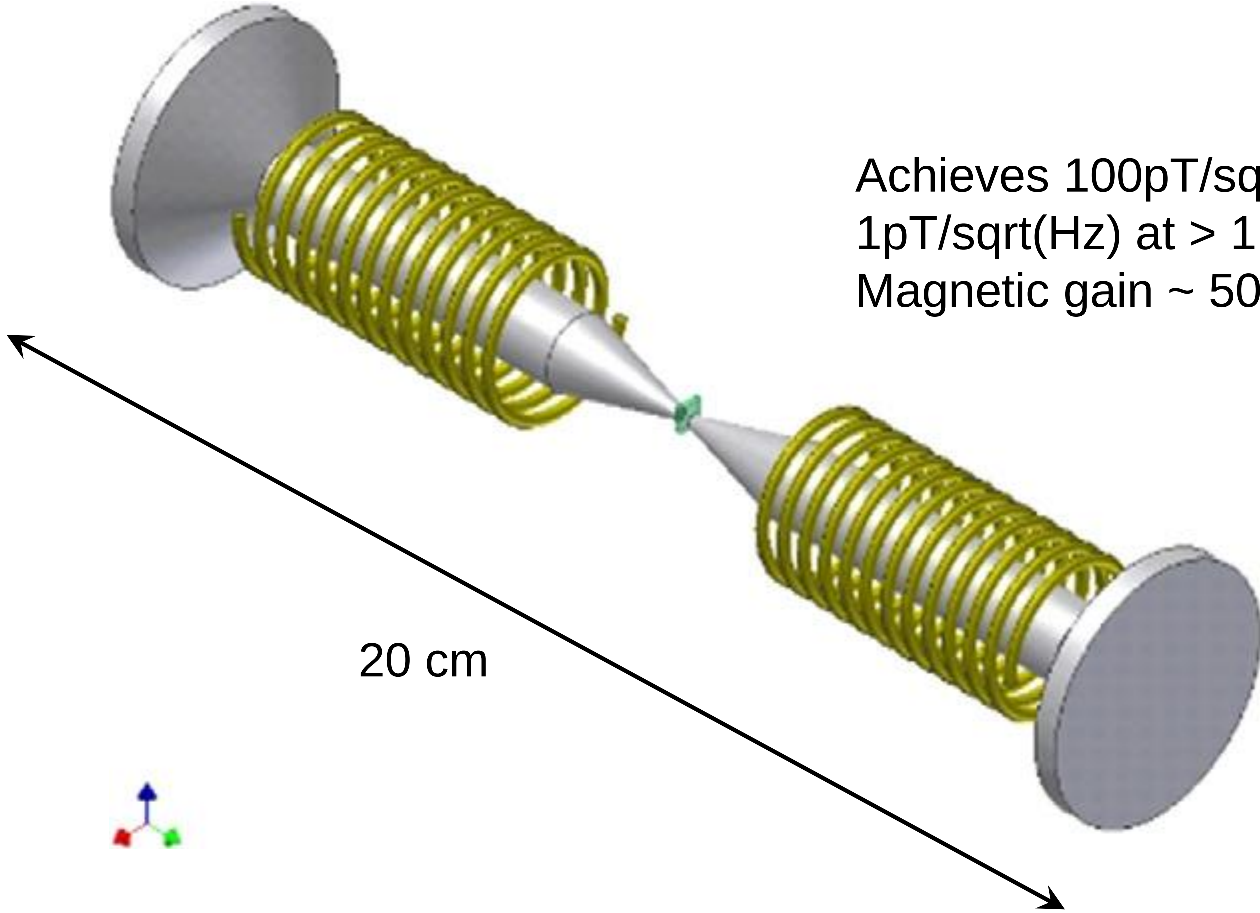


Note : GMR uses FC up to x100

Red line: QWHE sensor Sensitivity (No FC)

Fig. 9 GMR and QWHE sensors sensitivities

Combining Hall sensor and flux concentrator



Achieves 100pT/sqrt(Hz) at 1Hz and
1pT/sqrt(Hz) at > 1kHz
Magnetic gain ~ 500

P. Leroy et al Sensors and Actuators A 142 (2008) 503–510

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2 DEG Hall Effect Detection Sensitivity

Detection sensitivity depends on two factors:

(1) Scale factor in translating B (Tesla) to output signal voltage and

(2) noise that competes with the signal.

For 2DEG devices the scale factor is typically 1V/Tesla. The scale factor depends on bias current, which is limited by device dissipation to a few mW at maximum.

Dissipation and noise depends on the device resistance.

For our P2A sensor this gives a noise density of 3.4nV/root-Hz above 1kHz, rising at lower frequencies due to flicker noise. A good amplifier will have a noise density in the same region, typically 1-2nV/root-Hz. Obviously to get best sensitivity, we should operate the device with an AC field, if the application allows, and many do allow.

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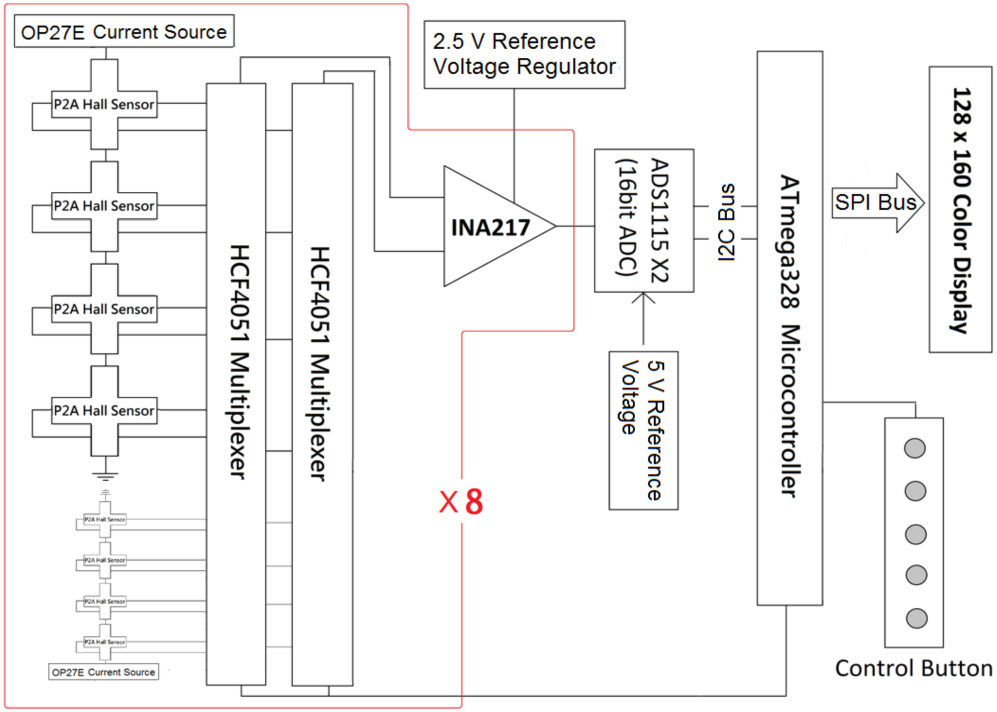
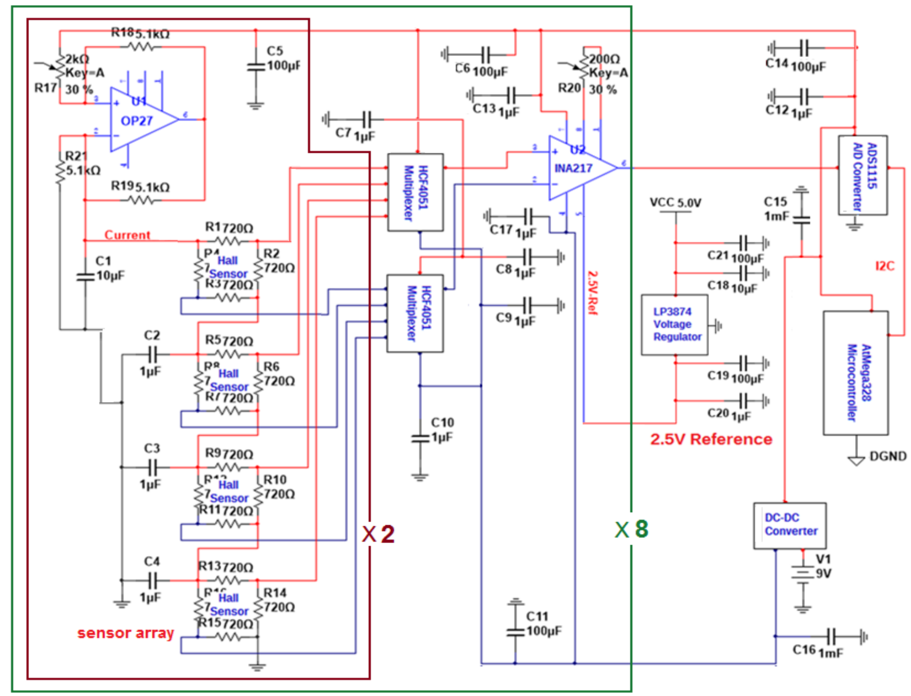
2D Magnetic Field Camera STFC B-Cam PROJECT (with WFS)

DC 2D array magnetometer design



Circuit design DC 2D array magnetometer



Schematic for DC 2D array magnetometer

DC 2D array magnetometer circuit layout

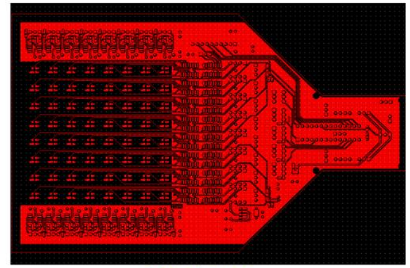
4 Layer PCB layout:

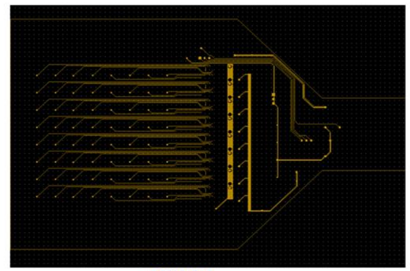
•<u>Top layer:</u>
Main components and most tracks for analog circuits

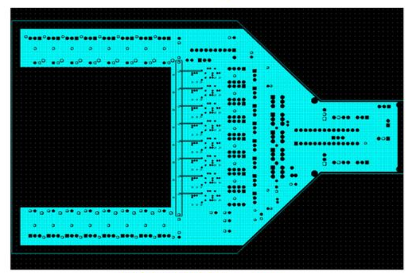
•<u>Mid layer:</u>
Most tracks for analog circuits

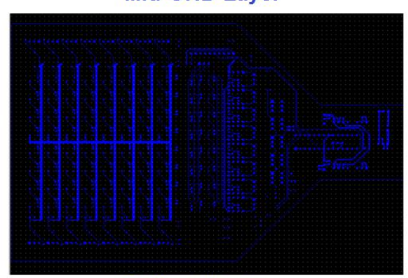
•<u>Mid-GND layer:</u>
Covered by analog ground

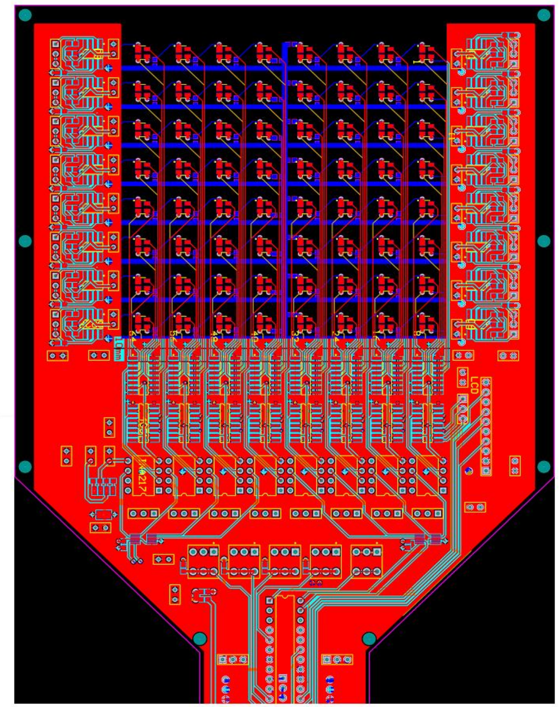
•<u>Bottom Layer:</u>
Surface mount capacitors and most tracks for digital circuits


Top Layer

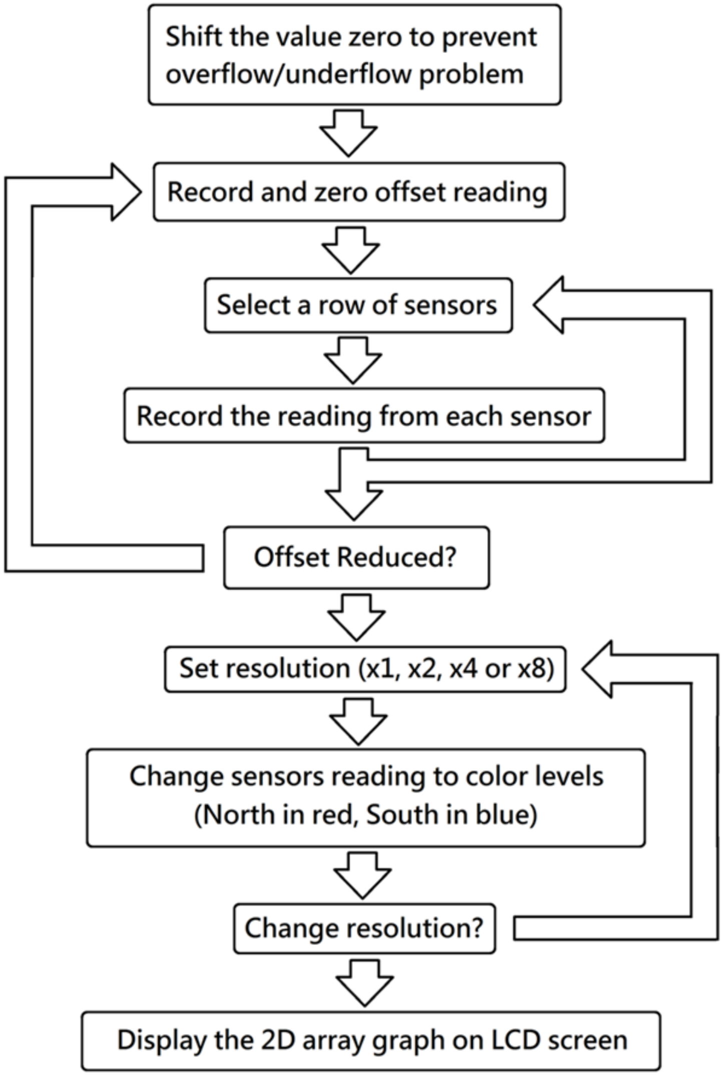

Mid Llayer

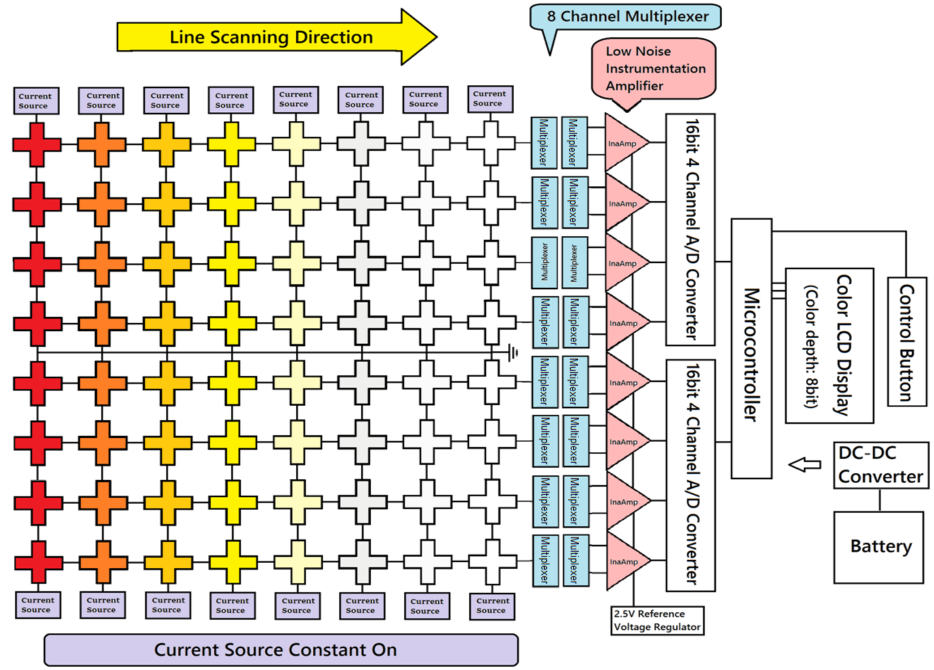

Mid-GND Layer


Bottom Layer


Top Layer
(Larger Picture)

DC 2D array magnetometer program flowchart

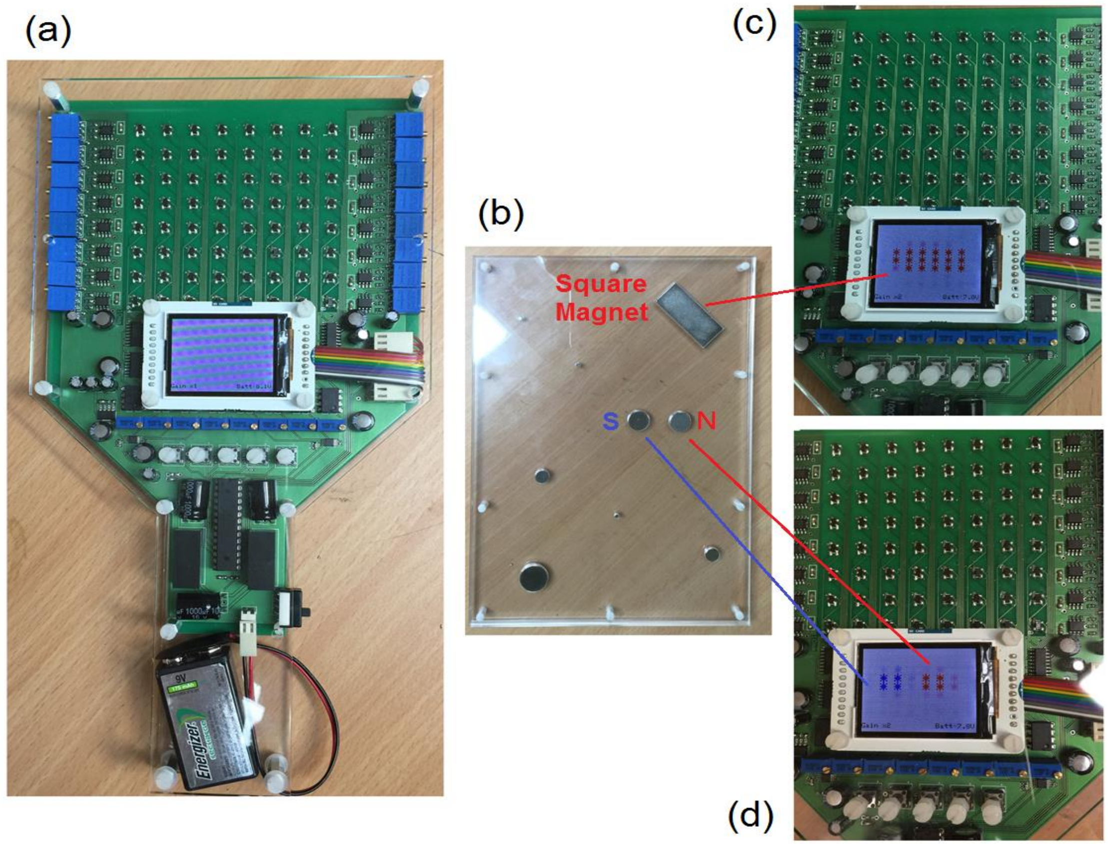




Program control of the scanning is a left to right cycle

Flowchart of micro-controlled DC 2D Hall array magnetometer

DC 2D array magnetometer prototype



Sensitivity test results of the DC 2D Hall array magnetometer are shown below, where gains of x1, x2, x4, and x8 are the levels with 24, 12, 6, and 3 μT icon^{-1}, respectively.

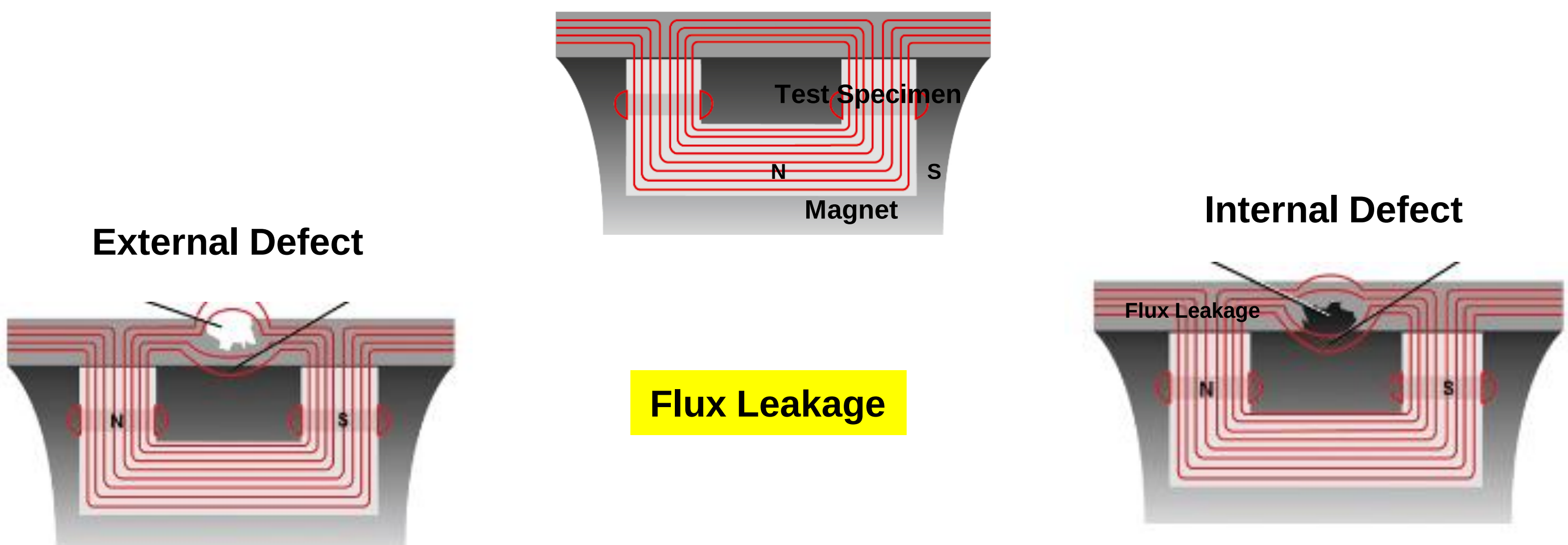
DC 2D 8x8x array magnetometer prototype with field visualisation

(a) (b) (c) (d)

Sensitivity test results of the DC 2D Hall array magnetometer, where the attenuations in (a), (b), (c), and (d) are 1/32, 1/16, 1/8, and 1/4, respectively

2D Magnetic Field Camera: MFL measurements

- Magnetic Flus Leakage (MFL) exploits the fact that magnetic flux lines which are usually confined to the interior of a magnetised material, breaks out (leak) from the confinement at the site of a defect or discontinuity



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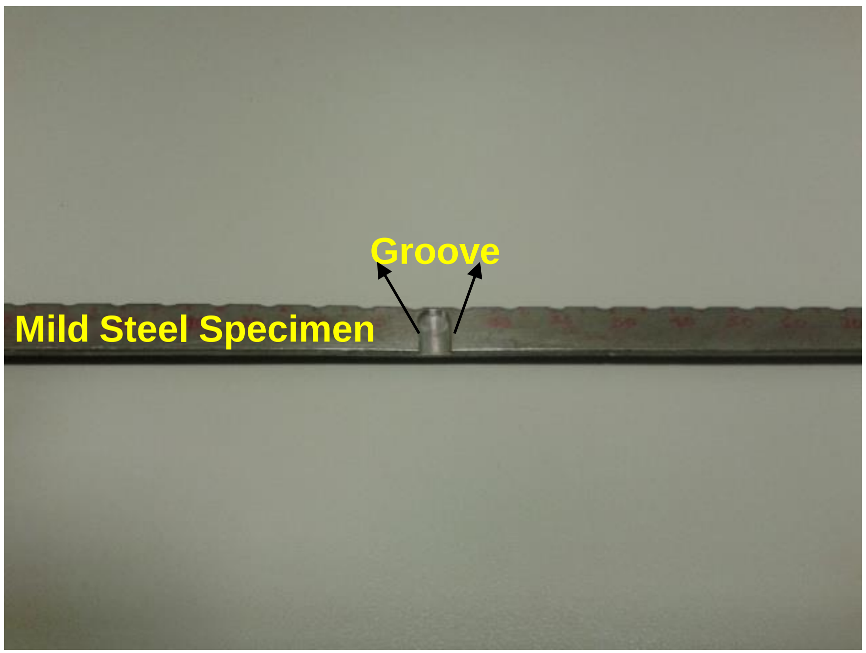
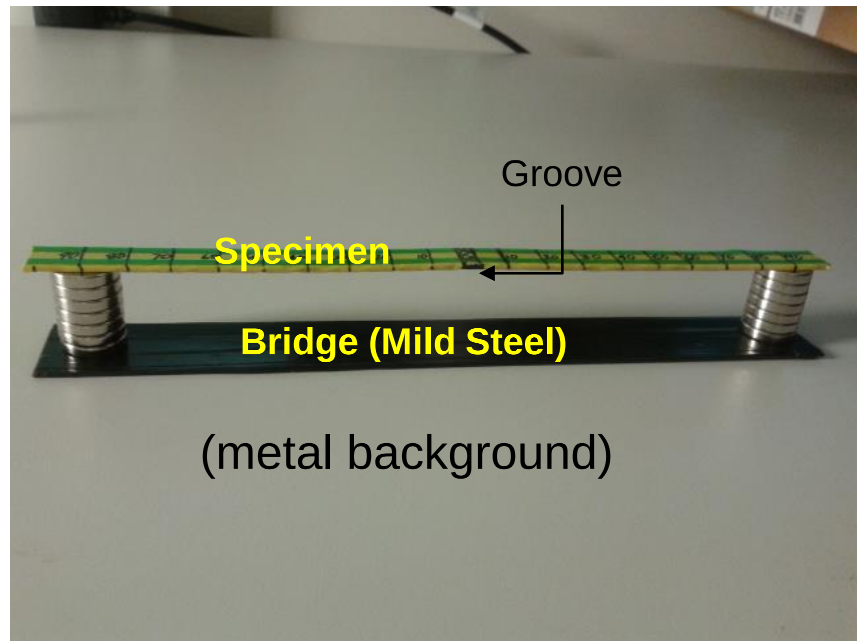
MFL Experimental set up

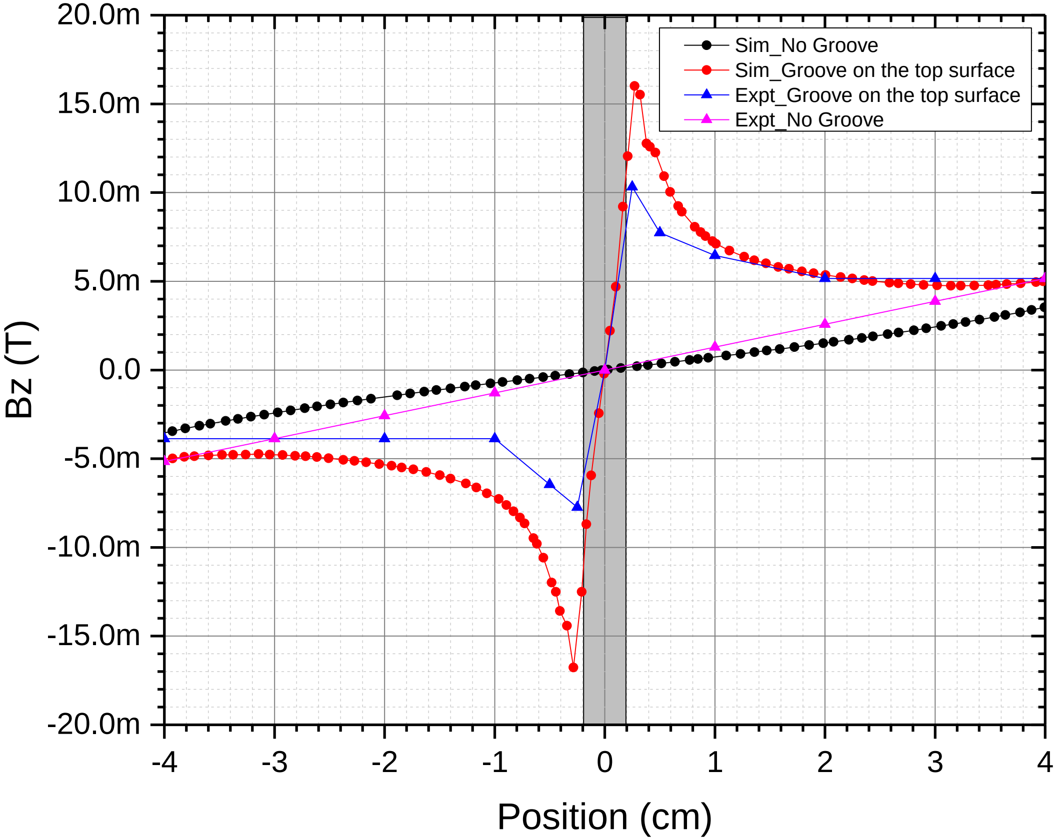




3D Magnetic Fields Simulation & Experimental results

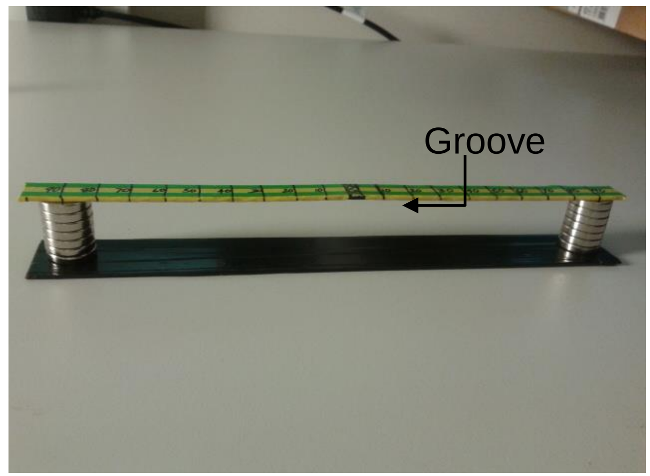
Flux Leakage:Simulation and Experiment

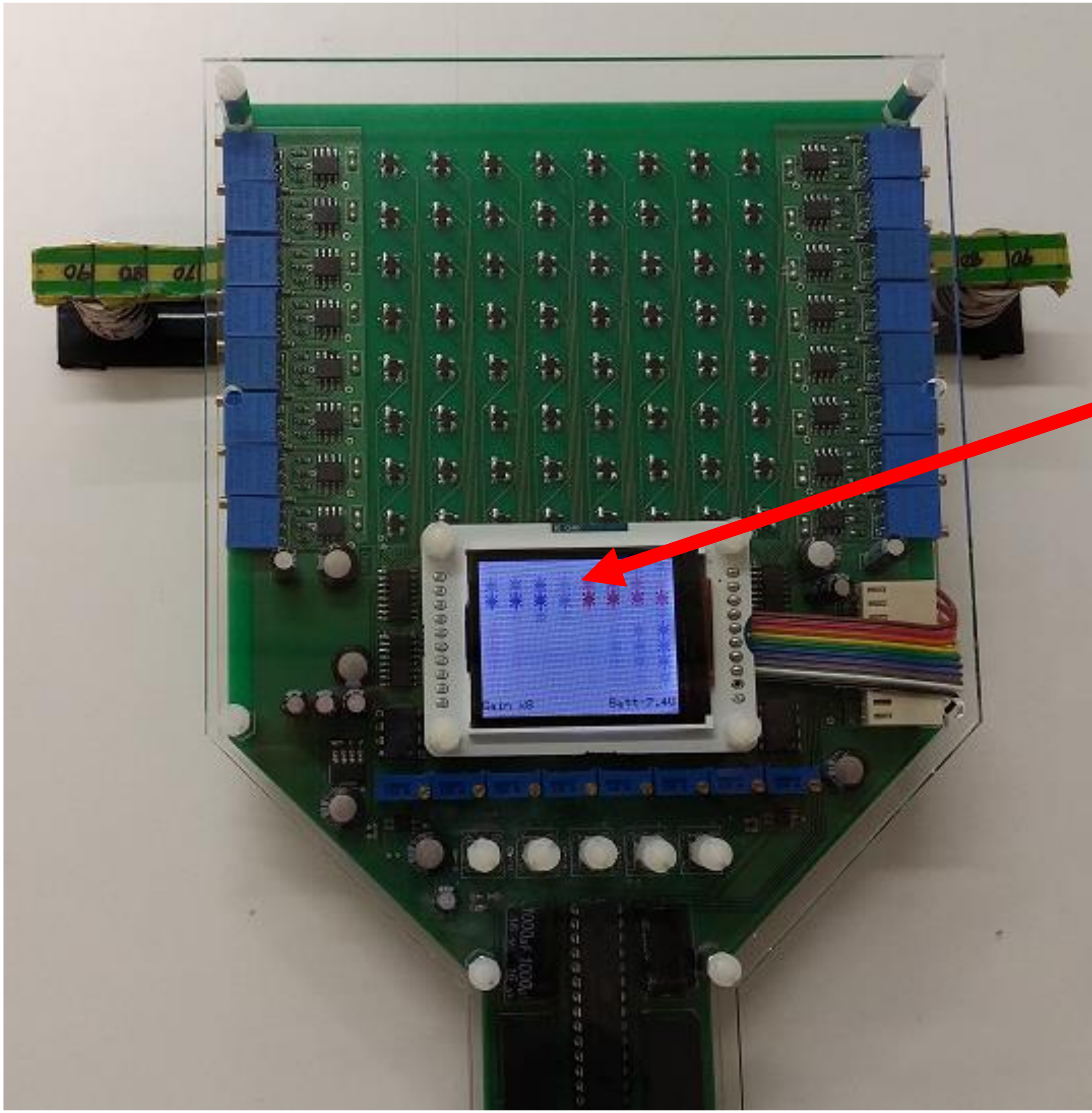
At the groove boundary



The predicted maximum value of Leakage Field ~ 16 mT

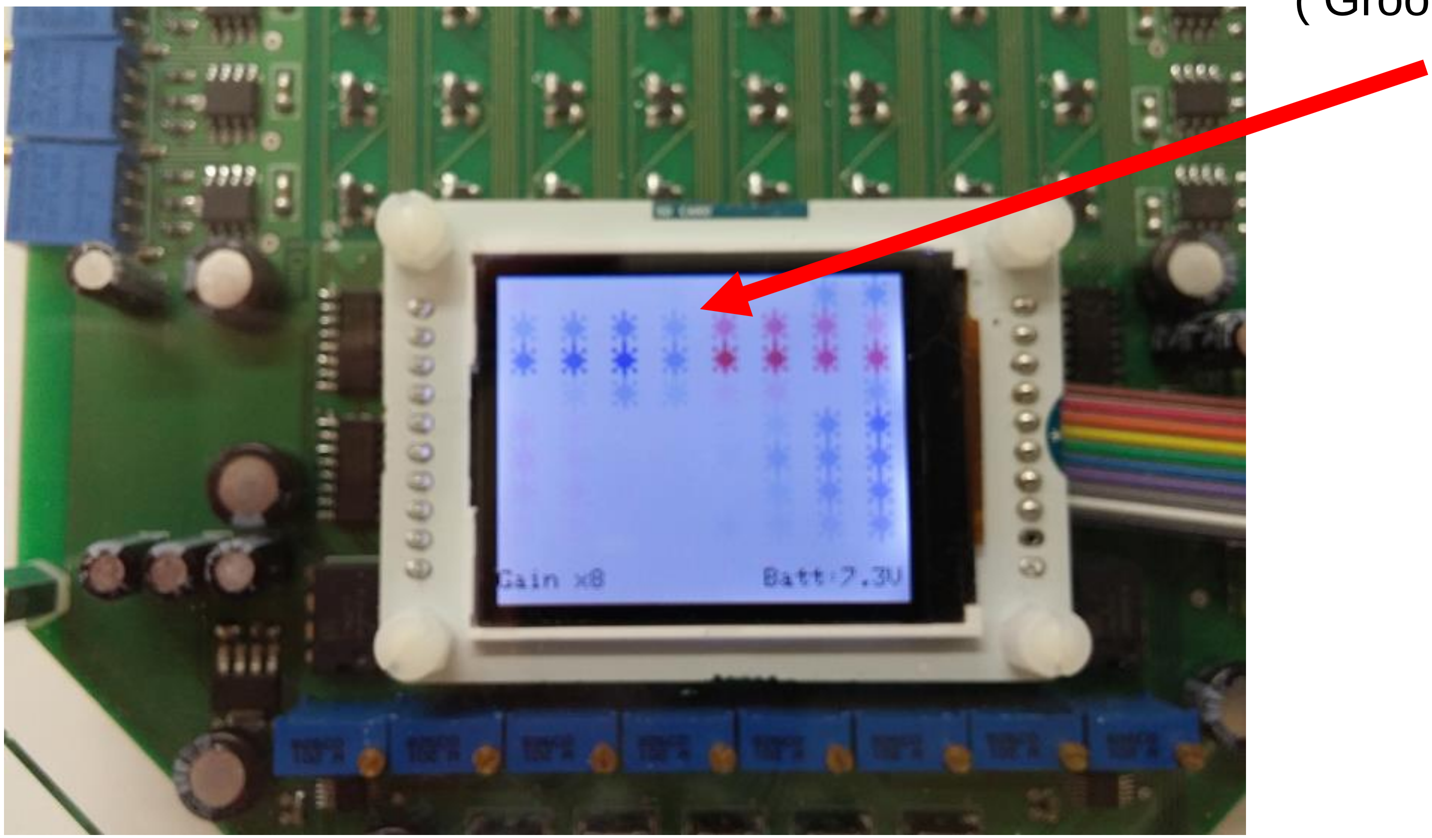
The experimental maximum value of Leakage Field ~ 9 mT





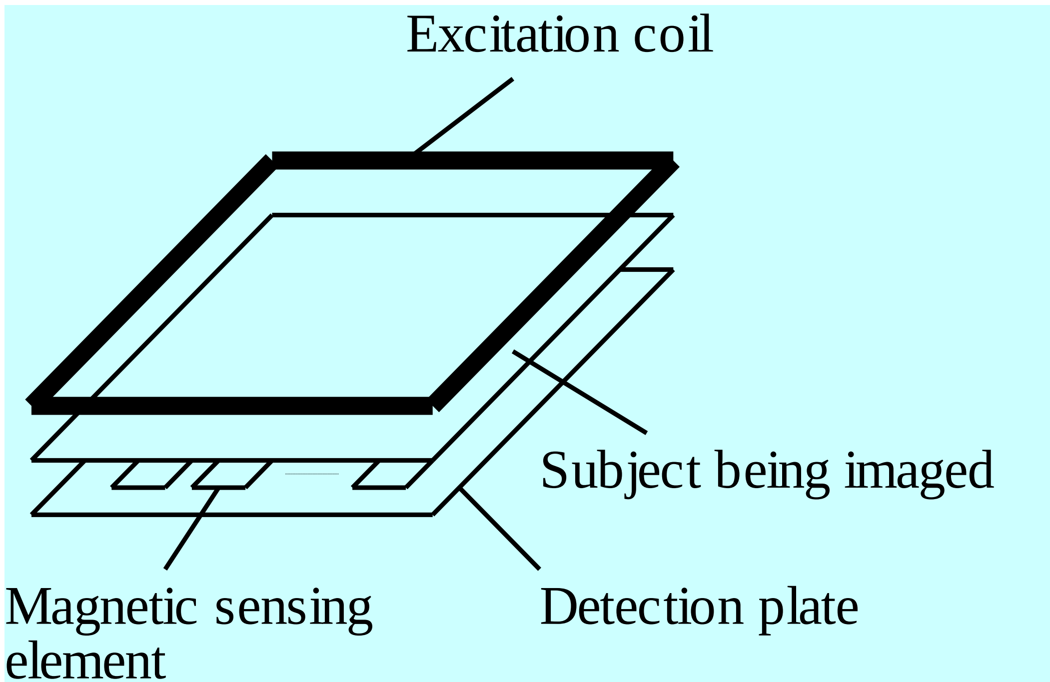
Field inversion
(Flaw position)

Field inversion
(Groove position)

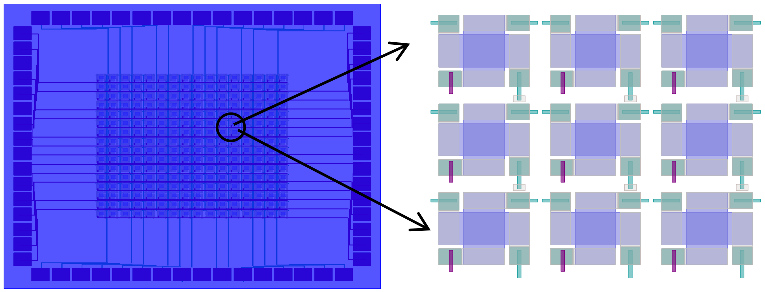


WHERE NEXT ?

2D array in NDT combining coils for scene illumination and 2DEG sensors for image capture (3D Dynamic Magnetic Vision).



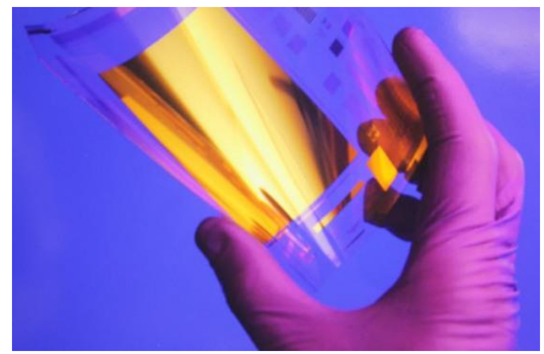
WHERE NEXT ?



Integrated 2D Arrays size ~ 1mm x 1mm

Sensor~ 2x 2 μm^2 to 20 x 20 μm^2 or larger

Integrated 2D ARRAYS with on board processing



Conformal sensing/Mapping
Convergence of high performance III-V electronics with Flexible Electronics

AHS

ISOQAR REGISTERED UKAS MANAGEMENT SYSTEMS 0026
Certificate Number 12762
ISO 9001

Spin out Company Advanced Hall Sensors (AHS)

CONCLUSIONS

- 2DEG AlGaAs/InGaAs/GaAs QW Hall sensors show promise in nanotesla magnetometery.

- Field resolutions of ~ 1 μT at DC and 20nT at 100kHz (1Hz bandwidth and room temperature) are possible.

- These Hall effect sensor can be used in banknote validations and magnetic domain imaging.

- High resolution 2D arrays are capable of rapid MFL measurements.

- 3D Dynamic imaging arrays a possibility for Eddy Current testing of conductive and composite materials.

- More improvement expected with even more advanced QWHE structures….

ACKNOWLEDGEMENTS

STUDENTS/PDRAs:

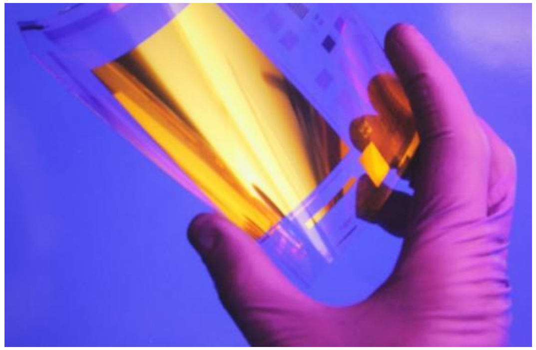
E. Ahmad, E. Balaban, M. Sadeghi, J. Sexton. C. Wei Liang and Z. Zhang

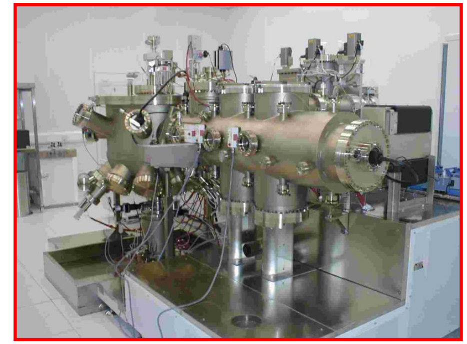
FUNDERS

1. STFC-ST/L000040/1 "HIGH RESOLUTION 2D MAGNETIC VISION- B-Cam " Nov2013-Oct2016."

2. TSB Technology Inspired CRD - Advanced Materials " High performance III-V semiconductor materials for magnetic Hall Effect sensors" Nov2013-October2015.

3. EPSRC "UK RESEARCH CENTRE IN NON-DESTRUCTIVE EVALUATION (RCNDE) 2014-2020" EP/L022125/1, Apr2-14-March2020





THANK YOU AND QUESTIONS?