Wide temperature range Hall effect sensors with minimal planar Hall effect

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Why Measure Magnetic Fields?

Does your product involve magnets or magnetic fields?

- Determine strength of generated field
- Determine location/presence of known magnets
- Determine strength of magnets

Encoder photo by Joao Paulo Chagas - Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=58020933
Analog magnetic sensors

- Focus on general purpose sensing technology, easily integrated into other equipment
- Excluding several great magnetic field sensing solutions that don’t fit this application

NMR image property of Metrolab Technology SA - https://www.metrolab.com/products/pt2026/
Fluxgate image from NASA public domain video - https://youtu.be/EWHIMBrIsGo
Some common ‘simple’ magnetic sensors

Magnetoresistance

- AMR
  - anisotropic
- TMR
  - tunneling
- GMR
  - giant

Hall effect

- InAs
  - Indium Arsenide
- GaAs
  - Gallium Arsenide
- InSb
  - Indium Antimonide

- AMR: Anisotropic Magnetoresistance
- TMR: Tunnel Magnetoresistance
- GMR: Giant Magnetoresistance
- InAs: Indium Arsenide
- GaAs: Gallium Arsenide
- InSb: Indium Antimonide

- Monolithic
- 3-axis
Magnetic field sensors – giant magnetoresistance (GMR)

- **Pros:**
  - Inexpensive
  - Good resolution
  - Long track record
  - Moderate temperature range

- **Cons**
  - Saturation
  - Hysteresis
Magnetic field sensors – tunneling magnetoresistance (TMR)

Pros:
- Excellent resolution
- Small
- Moderate cost
- Moderate temperature range

Cons
- Saturation
- Hysteresis

Typical magnetoresistance of tunnel junction
Liu et al. J. Appl. Phys., Vol. 92, No. 8, 15 October 2002
Magnetic field sensors – Hall

- **Pros:**
  - Simple
  - Linear
  - No hysteresis
  - Well established
  - Inherently directional
  - Very wide field range
  - Various materials available for different needs

- **Cons:**
  - Relatively large active areas
  - Resolution lower than GMR, TMR
  - Planar Hall Effect

Structure and Application of Galvanomagnetic Devices, H. Weiss, 1969
Planar Hall effect (PHE)

- Due to in-plane field component
  \[ V_{PHE} \propto B^2 \sin(2\phi) \times I \]

- Can be minimized by choosing sensor material properties

Structure and Application of Galvanomagnetic Devices, H. Weiss, 1969
Active area

What is an active area?

- Portion of the sensor that contributes to Hall voltage when a magnetic field is present
- Somewhat difficult to precisely define
- Smaller = better
Sensitivity

- Rate of change of Hall voltage vs applied field
- Usually presented in one of the following:
  - mV/kG
  - mV/T
  - V/AT (takes drive current into account)
- Higher sensitivity provides better measurement resolution
Linearity

- Ideally want to have as linear as possible
- May not be symmetrical from positive to negative fields
- Generally, lower sensitivity sensors have better linearity
- Most important at high fields
Non-uniformity in Hall sensor results in a small amount of Hall voltage even at zero field

- Offset voltage may change over time
- Most important at low fields.
Introducing 2-dimensional electron gas

Just what it sounds like:

- A sheet of electrons so thin that it can be considered 2-dimensional
- Usually shortened to 2DEG
- Demonstrate great Hall effect properties

WARNING: Quantum mechanics ahead

https://xkcd.com/1240/
Background

- Cartoon III-V Molecule
- Cartoon III-V Molecule (smaller bandgap)
- 2DEG
- Substrate
- Polarization doping
Introducing 2Dex™ Hall sensors

- Pedigree as a proven technology high-performance electronics
  - Established tech with well known performance and manufacturability
  - High-temperature, robust recipe that extends temperature and operating conditions for demanding applications

- Reduced planar Hall effect
- Equivalent sensitivity
- Better linearity
- Small offset voltages
- Smaller active area
Planar Hall effect (PHE)

- Driven by materials properties
- Can be minimized through material system design
- Initial measurements show PHE is within measurement noise for 2Dex sensors, lower than typical for n-type semiconductors commonly used for Hall sensors.
- Extremely useful for measuring large fields with unknown direction.
Active areas

Lake Shore
Instrument-grade
InAs sensors
Temperature Variation

2Dex Sensitivity Change with Temperature

Temperature (K)
## Hall sensors compared

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity at nominal drive (mV/T)</th>
<th>Linearity</th>
<th>Offset voltage (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAs</td>
<td>1</td>
<td>1%</td>
<td>0.05</td>
</tr>
<tr>
<td>2Dex</td>
<td>0.5</td>
<td>0.5%</td>
<td>0.05</td>
</tr>
<tr>
<td>GaAs</td>
<td>3</td>
<td>2%</td>
<td>2 to 10</td>
</tr>
<tr>
<td>InSb</td>
<td>3000</td>
<td>?</td>
<td>6 to 10</td>
</tr>
</tbody>
</table>
And for the material researchers in the audience

Quantum Hall effect!

- Additional oscillating non-linearity
- Largest at high field, cryogenic temperatures
- Usually difficult to see, but the improved linearity of 2Dex sensors allows us to observe it more easily
- Data from National High Magnetic Field Lab
- Up to 18 T and down to 4.2 K to fully characterize the effect
Cryogenic effects on Hall Voltage

Hall Voltage @ 4.2 K

- Field (T)
- Hall Voltage (V)
- Hall Voltage (mV)

2DEx
InAs

Lake Shore Cryotronics, Inc.
Cryogenic effects on Hall Voltage

Quantum Oscillations at 4.2 K

- Oscillation Non-linearity (mT)
- Applied Field (T)

2DEX and InAs
Cryogenic effects on Hall Voltage

Effect not significant unless:
- Field is greater than 6 T; and
- Temperature is below 30 K (liquid nitrogen = 77 K)
Drive circuits

Hall devices are fairly easy to drive if rudimentary measurements are required.

Accurate and precise measurements require more complex circuitry:
- Current reversal or current spinning to remove offsets
- Adjustable gain for different field ranges
- Non-linearity compensation
- Temperature compensation
- Post measurement data processing such as averaging, pulse detection and AC filtering
Gaussmeters/teslameters
F41 and F71 teslameters

Designed to work together with the new 2Dex™ sensors for trouble-free measurements:

- Non-linearity compensation
- Temperature compensation
- Frequency compensation

TruZero™ technology

- Continuously monitors and cancels out offset errors, while also reducing measurement noise
- Never zero a probe or sensor again

Come see the new teslameter at booth 204
Possible future developments for 2Dex™

- Cryogenic hermetic package capable of operation in high-stress environments
- Miniaturized active areas from 0.1 to 0.002 mm²
- SOIC package for PCB mounting
- Quantum oscillation reducing variant
Summary

2Dex™ Hall sensors

- Equivalent sensitivity
- Improved linearity
- Small offset voltages
- Reduced active area size
- Reduced planar Hall effect
- Wider temperature range

Thank you for your attention

Questions?