# Silicon Carbide magnetoresistive magnetometer with electrically detected magnetic resonance self-calibration feature for space science applications

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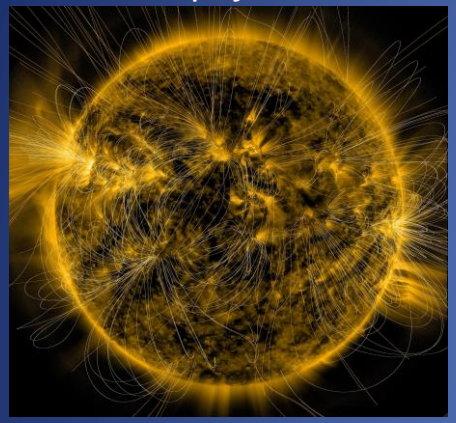
# This Work

- Overview of the initial stages of development for a new solid-state based magnetometer intended for vectorized planetary magnetic field sensing.
  - It utilizes a single Silicon Carbide (SiC) transistor
    - Wide bandgap: Robust in high temperature and high radiation environments
    - One sensor needed for simultaneous measurement of three axes
    - Can be made extremely small and requires very little power
  - Leverages intrinsic defects which play a role in spin dependent recombination
  - Has potential for self calibration and redundancy field measurement
- Demonstrated sensitivity of $440\ nT/\sqrt{Hz}$ with potential to go well below $1\ nT/\sqrt{Hz}$ with customized sensor design.

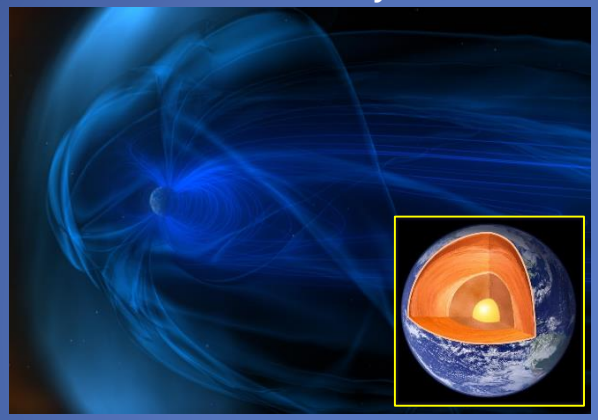
# NASA's Interest in Magnetometers

## Magnetic fields are encountered everywhere is space

Heliophysics

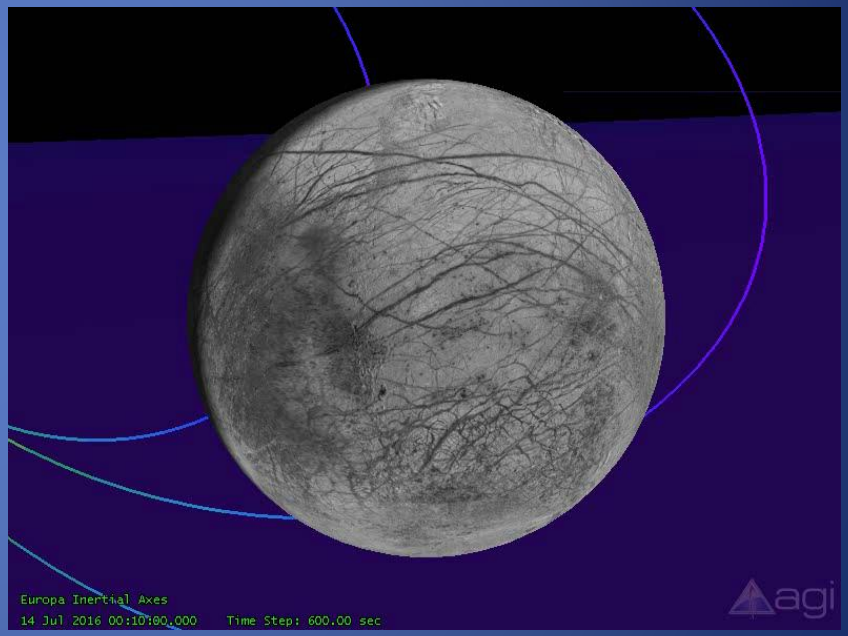


Earth & Planetary Science



## Geomagnetic field models highly rely on magnetometer data

Europa / Jupiter




Simulation:
JPLs Jupiter Environment Tool (JET) plugin for STK
Erick Sturm, Corey Cochrane

## Magnetometers aid in the search for life

Europa/Jupiter

Enceladus/Saturn

Image credit: NASA

# Motivation for New Technology

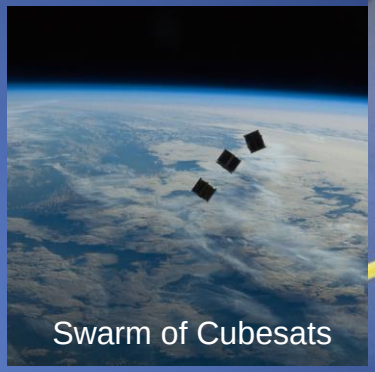
## 1. Miniaturization & lower cost

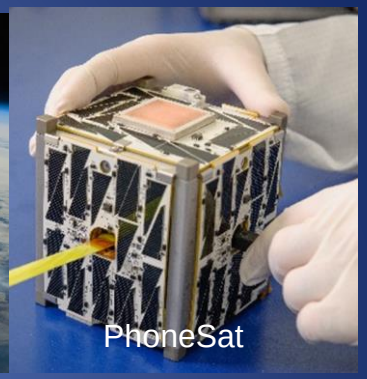
MAVEN

fluxgate

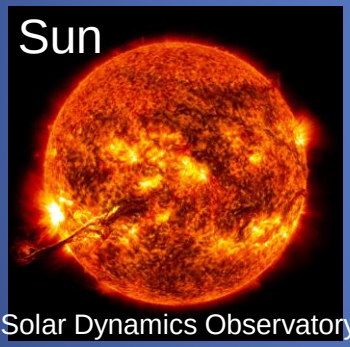
Pioneer 10/11

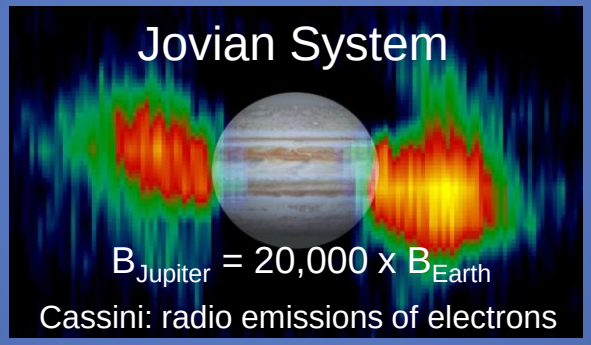
optically pumped

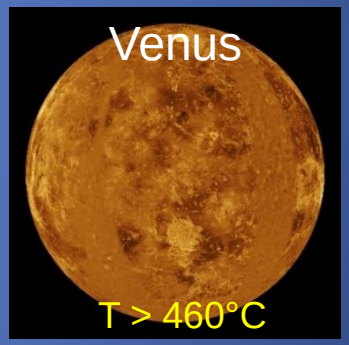



## 2. Extreme Environments

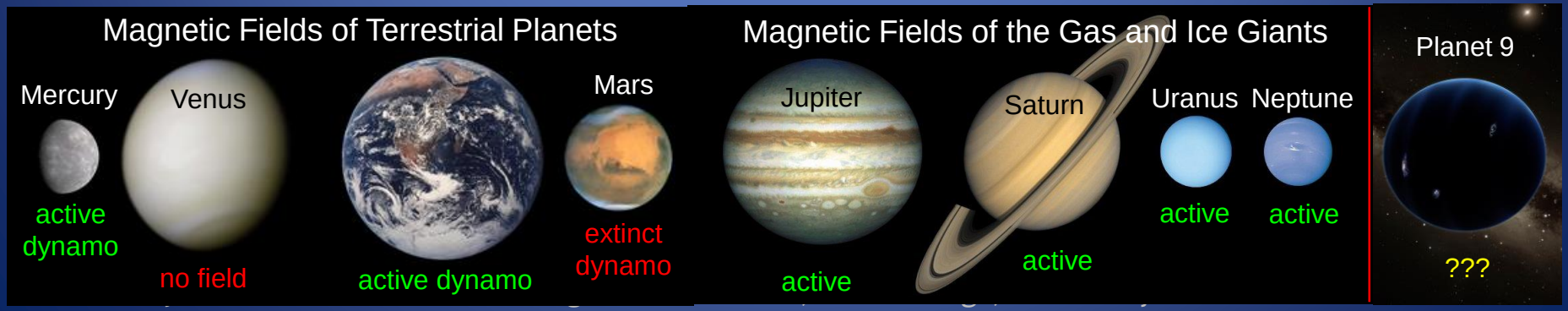


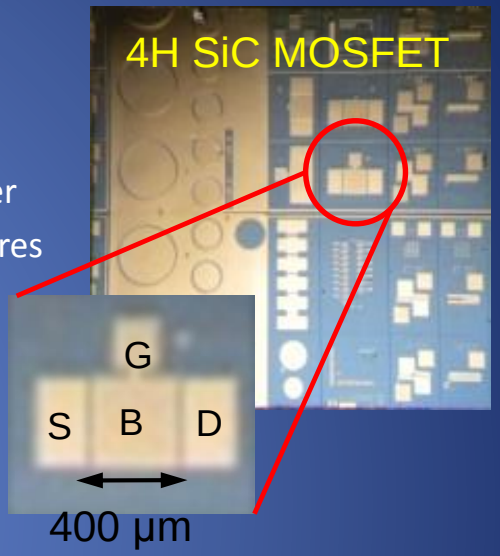

## 3. Still much science to be obtained!

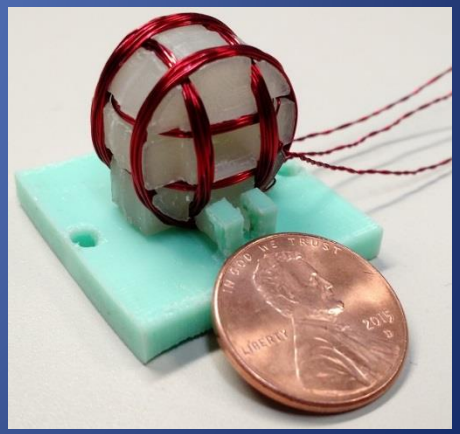
http://nssdc.gsfc.nasa.gov/planetary/factsheet/



# SiC Magnetometer (SiCMag)

- Solid state:
  - Purely electrical interface, digital output
- Simple:
  - Field nulling design: Inexpensive, simplistic design, small footprint, low power
  - no high frequency RF or optical components which require stable temperatures
  - No dead zones
  - Simultaneous measurement of three axes using only a single sensor
- Magnetic field modulation:
  - Significantly reduces 1/f noise observed from DC current
  - Prevents DC sensor current drift
  - sharp zero-crossing (1st harmonic) or well defined peak (2nd harmonic)
  - performed in software via computer, microcontroller, or FPGA
  - Allows for vectorized magnetic field sensing
  - Modulation waveform can share the same set of Helmholtz coils as DC cancelling signal because audio frequencies used
  - Allows for detection of electron-nuclear hyperfine interactions
- 4H SiC diode sensor:
  - Large bandgap (> 3eV): inherently rad hard and high temp environments
  - Crystalline lattice allows for sharper signals to be detected,
  - Magnet nature of dopant (B, Al, N, P) and host atoms (Si, C) allow it to be self-calibrating due to electron-nuclear hyperfine interactions

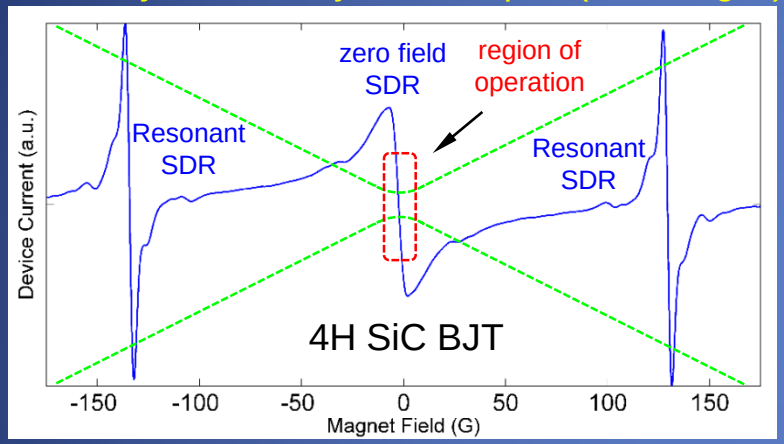


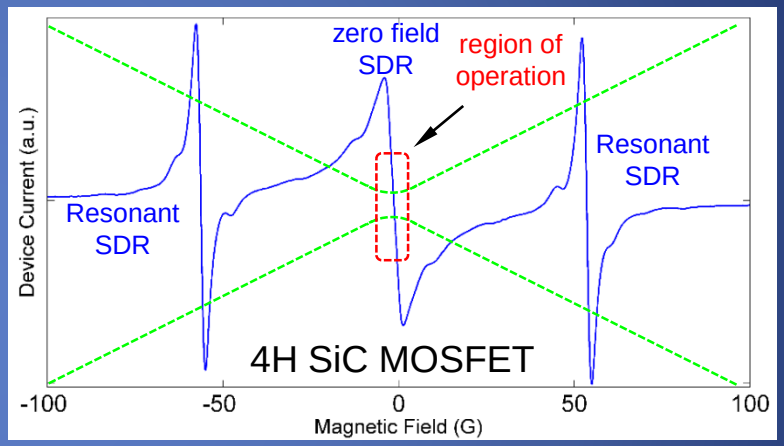
# Origins of Technology: Low-Field EDMR in SiC

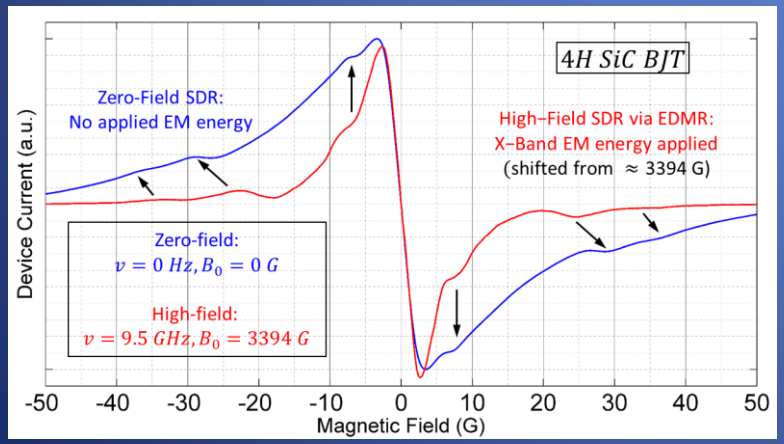
The size of the EDMR effect is not dependent on magnetic field strength
Can be performed at low magnetic fields without loss of signal amplitude.

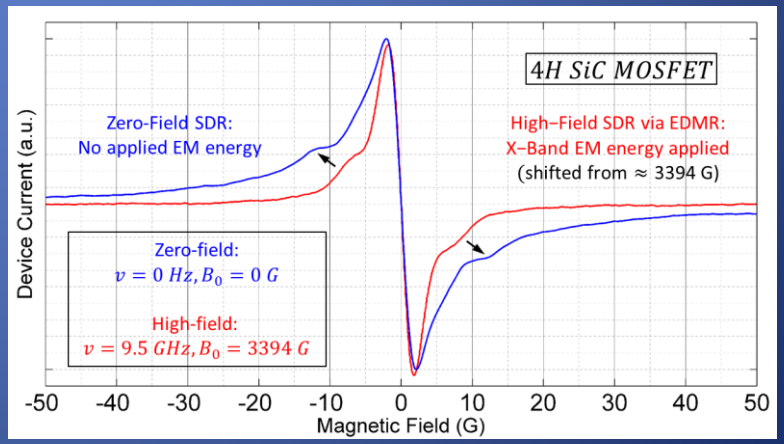
Divacancy or Vacancy/Anitisite pair (Involving N)




Silicon vacancy located at the $SiC/SiO_2$ Interface



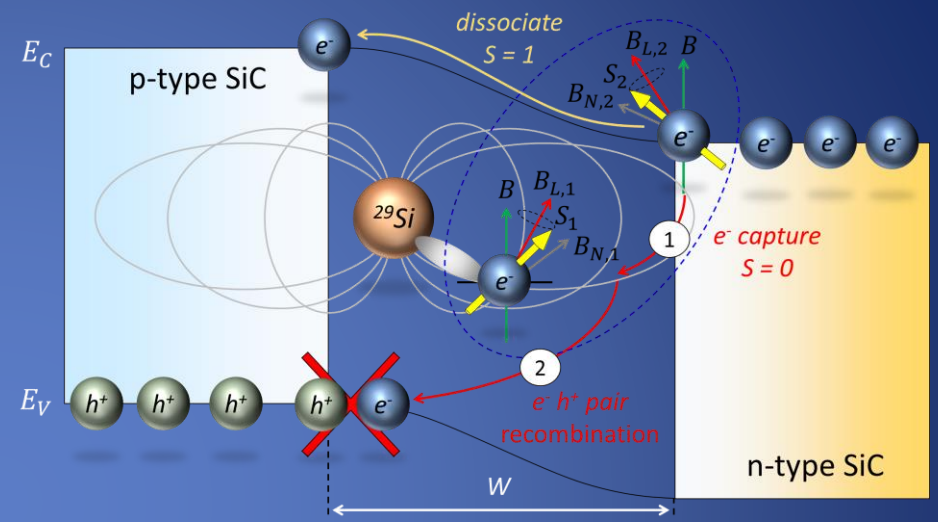




C.J. Cochrane, et al., *Journal of Applied Physics*, 112, 123714 (2012).

# Spin Dependent Recombination (SDR)

- In SDR, conduction electrons may couple with electrons within deep level defect electrons to form singlet and triplet pairs.
- Because recombination involves zero change in angular momentum, only electrons of singlet pairs will recombine while triplet pairs dissociate.
- In the presence of a external magnetic field, application of electromagnetic energy flips the spins of the electrons which converts triplet pairs in to singlet pairs, thereby allowing a change in current to be detected at the resonance condition of the defect.



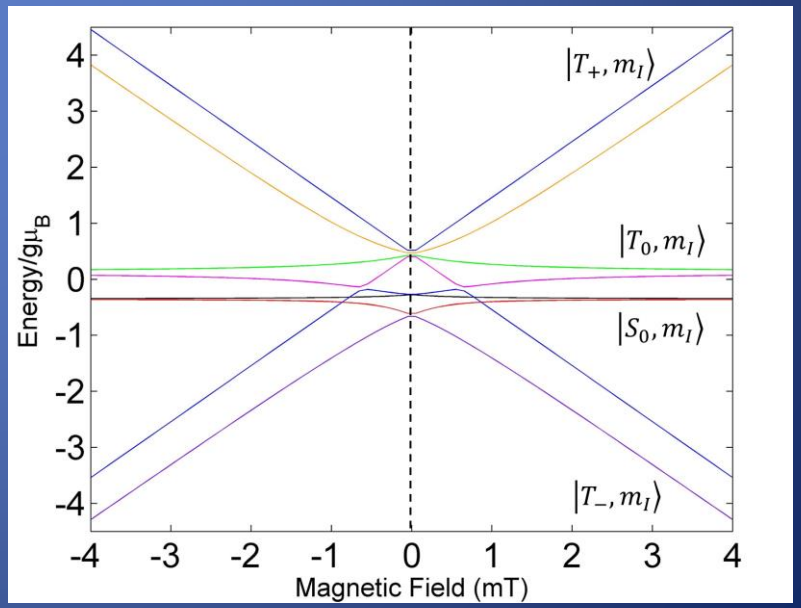

$$\mathcal{H} = g_e \mu_B \boldsymbol{B} \cdot (\boldsymbol{S}_1 + \boldsymbol{S}_2) + \sum_i^2 \sum_j^N \boldsymbol{S}_i \cdot \boldsymbol{A}_{i,j} \cdot \boldsymbol{I}_j + \boldsymbol{S}_1 \cdot \boldsymbol{J} \cdot \boldsymbol{S}_2 + \boldsymbol{S}_1 \cdot \boldsymbol{D} \cdot \boldsymbol{S}_2$$

If $N = 1$ with $I = 1/2$,

$$\langle \downarrow, S_0 | \mathcal{H} \, | T_+, \uparrow \rangle = \frac{\Delta A_y - \Delta A_x}{4\sqrt{2}} \qquad \langle \uparrow, S_0 | \mathcal{H} \, | T_+, \downarrow \rangle = -\frac{\Delta A_y + \Delta A_x}{4\sqrt{2}}$$

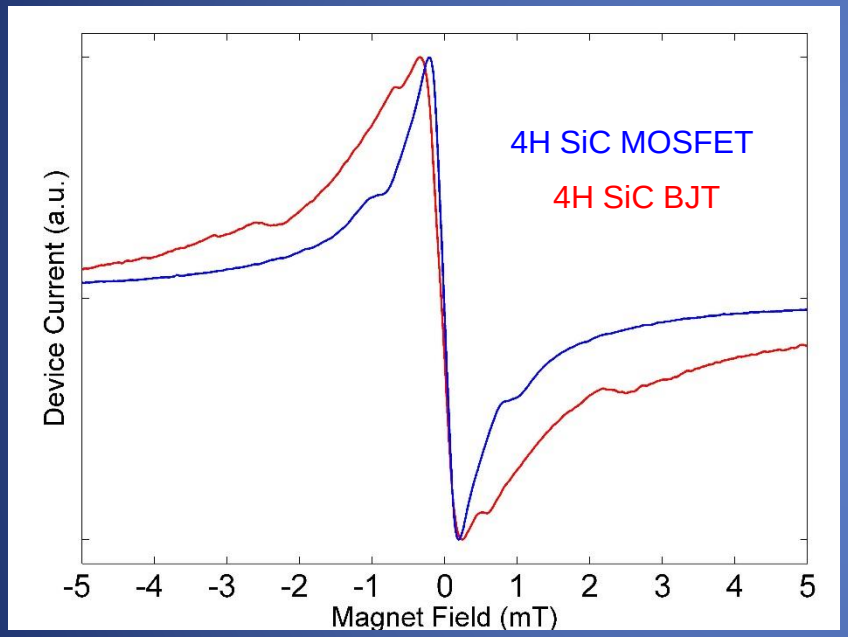
$$\langle \downarrow, S_0 | \mathcal{H} \, | T_-, \uparrow \rangle = \frac{\Delta A_y + \Delta A_x}{4\sqrt{2}} \qquad \langle \uparrow, S_0 | \mathcal{H} \, | T_-, \downarrow \rangle = \frac{\Delta A_x + \Delta A_y}{4\sqrt{2}}$$

$$\langle \uparrow, S_0 | \mathcal{H} \, | T_0, \uparrow \rangle = \frac{\Delta A_z}{4} \qquad \langle \downarrow, S_0 | \mathcal{H} \, | T_0, \downarrow \rangle = -\frac{\Delta A_z}{4}$$

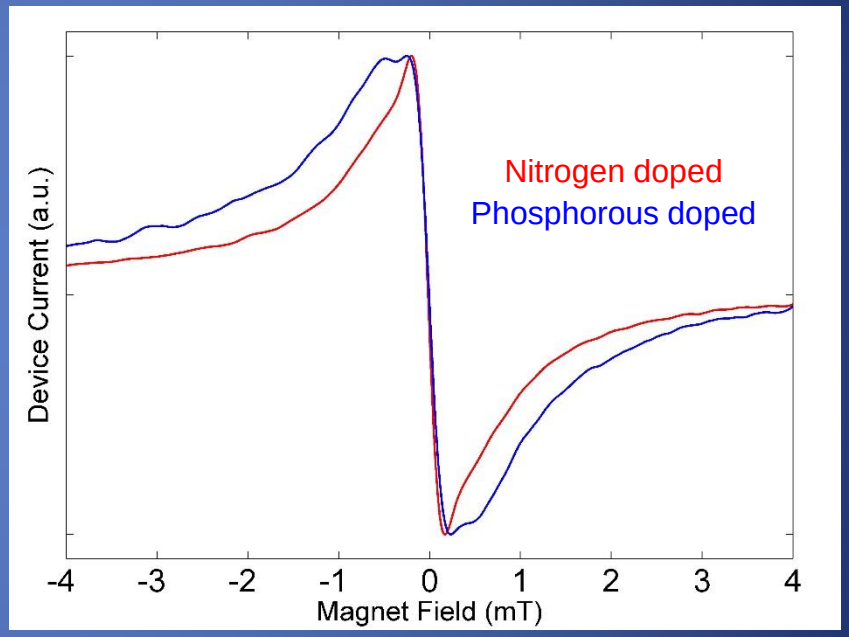


# Device Profiles

4H SiC Devices from Cree




4H SiC Diodes from NASA Glenn




The "as processed", 4H SiC nMOSFET had the sharpest and highest SNR of the four devices measured.

# Estimated Sensitivity

The theoretical sensitivity is

$$\frac{\delta B}{\sqrt{\Delta f}} = 2\sigma\sqrt{\pi q}\frac{\sqrt{I_0}}{\Delta I}\left(\frac{T}{\sqrt{Hz}}\right)$$

W.J. Baker, et. al, "*Nature Communication*, **3**, 898, (2102).

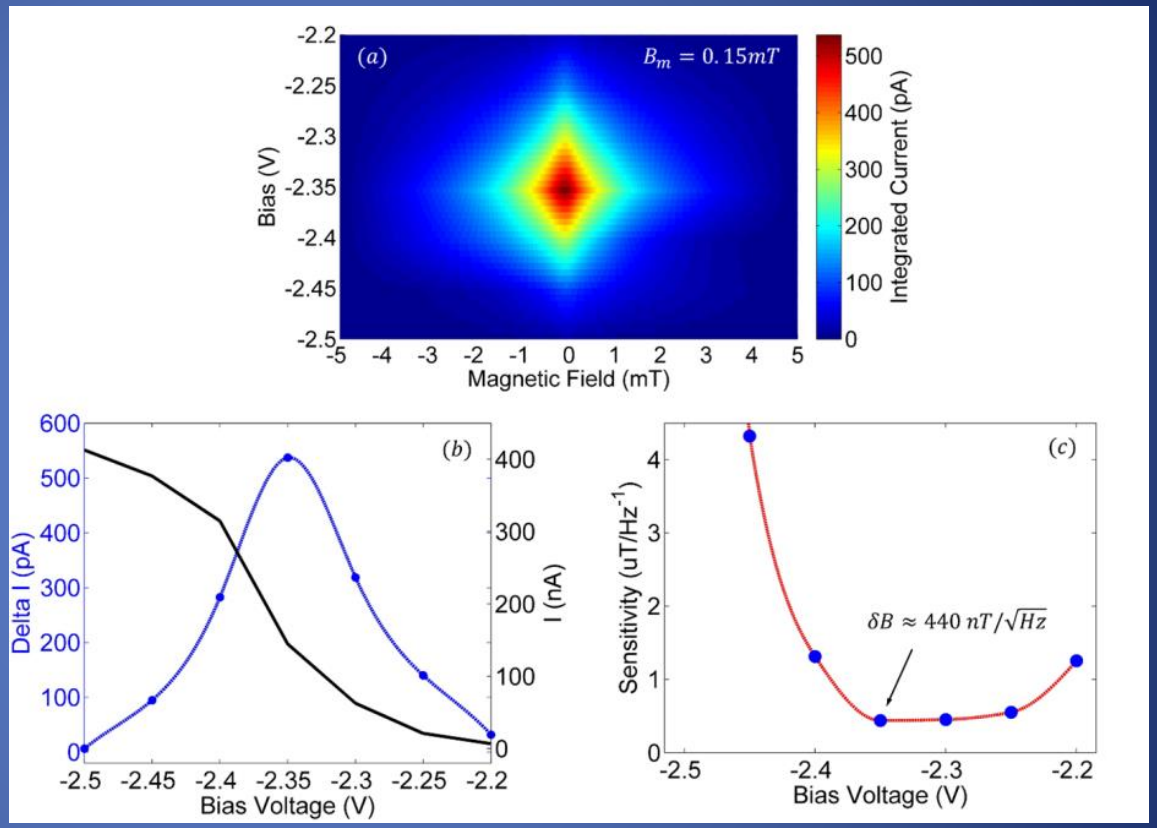
Measurements of the data set

$DC\ current\ I_0 = 145\ nA$

$change\ in\ current\colon\ \Delta I = 540\ pA$

$signal\ width\colon\ \sigma = 0.4\ mT$

$$\frac{\delta B}{\sqrt{\Delta f}} = 440\frac{nT}{\sqrt{Hz}}$$



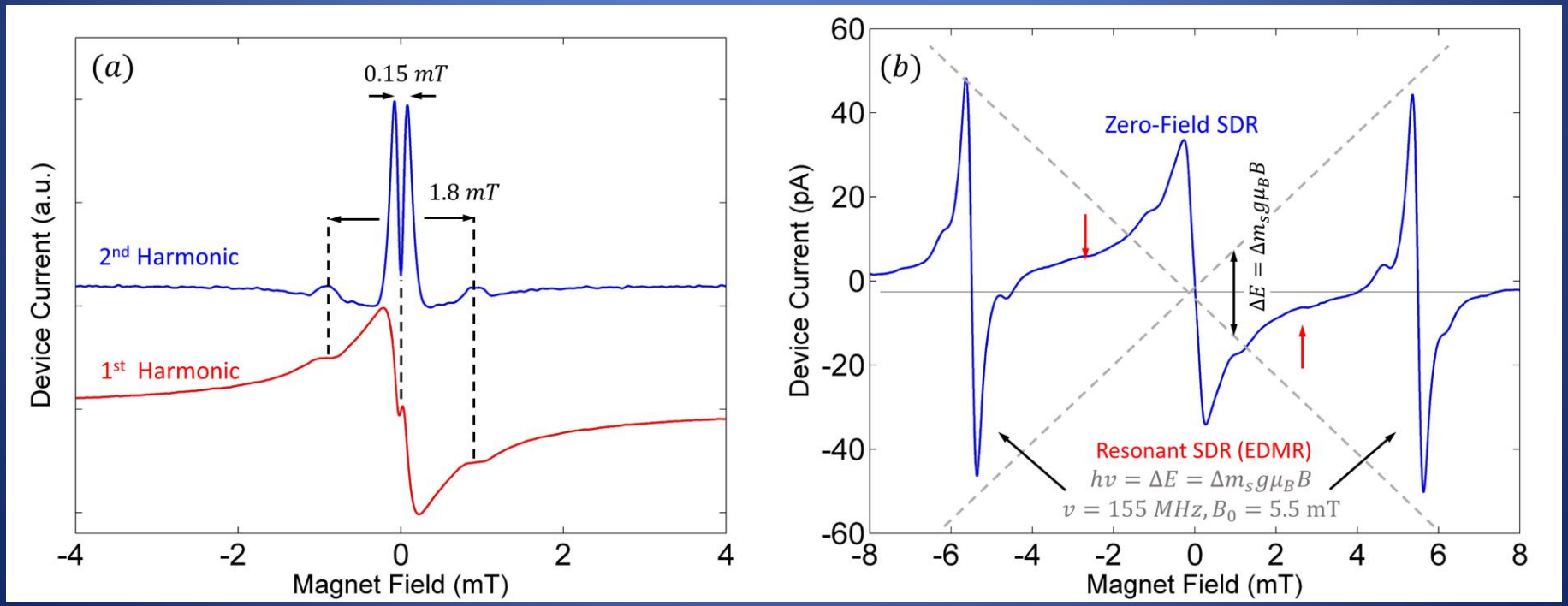

NOTES:

- Devices intended for power electronics and not magnetometry!
- Very easy to decrease $I_0$ and increase $\Delta I$.
- Fluxgates and Helium magnetometers have more than 50 years of development.

# Self-Calibration & Redundancy Measure

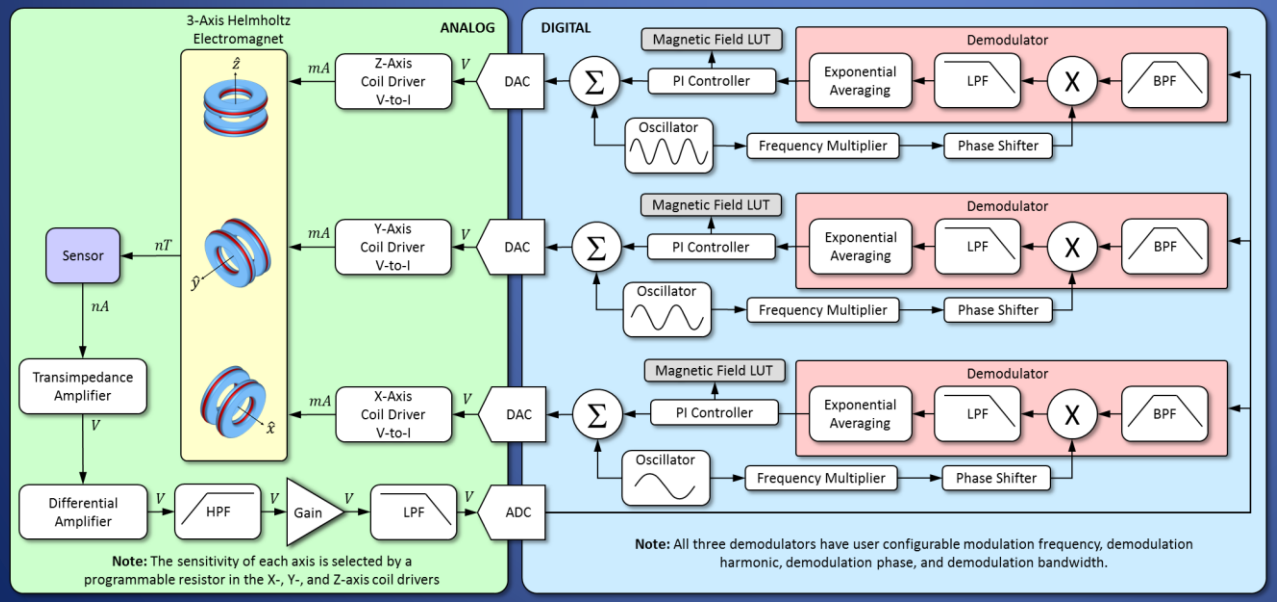
Self-calibration: The bias and modulation dependent inflection points produce sharp derivative features in the second harmonic which may serve as stable magnetic field markers to self-calibrate the magnetometer.

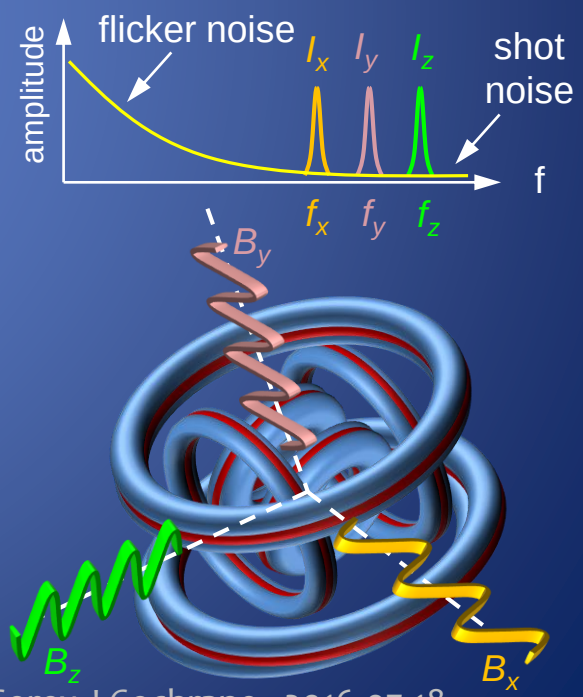
Redundancy: EDMR approach can also be easily incorporated used to provide a redundant magnetic field measurement by adding an offset field and a small coil/resonator to monitor resonant SDR.



# Magnetometer Operation

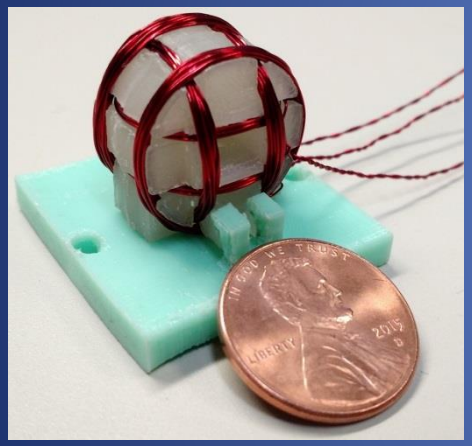
- SiC diode is placed inside a network of Helmholtz coils, one set for each axis.
- Each coil modulates the external magnetic field (orthogonal audio waveforms) which frequency division multiplexes the components onto a single channel.
- The conditioned sensor current is digitized and fed through three independent software demodulators to extract the embedded current components
- A controller then tracks the zero crossing of these components and pumps each Helmholtz coil with the required current needed to maintain region of zero magnetic field across the sensor.



# Vectorized Demonstration

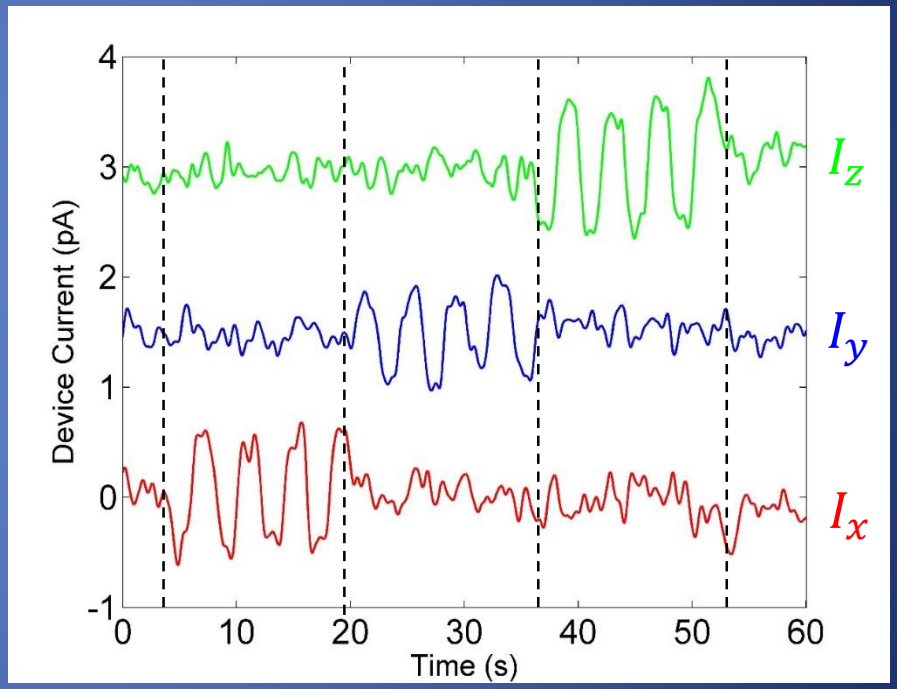
3D Printed,
3-axis Helmholtz coil



Magnet fabrication:
Gerardo Hernandez,
JPL Summer Intern

3-axis Helmholtz coil
within Mu metal
shielded chamber

+/- 1500 nT square wave applied to each axis
(NOTE: Earth's field 50,000 nT)




$$\frac{\delta B}{\sqrt{\Delta f}} = 440 \frac{nT}{\sqrt{Hz}}$$

# Applications and Future Work

- Applications
  - planetary entry probes
  - Landers
  - missions in extreme environments
  - swarms of spacecraft significantly smaller than current nanosats

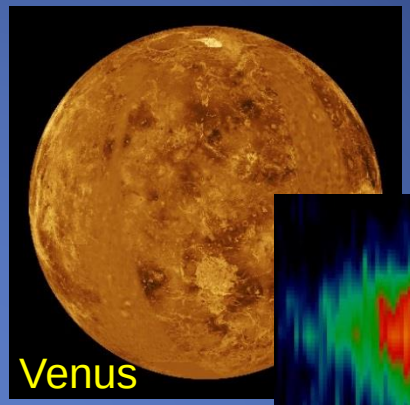
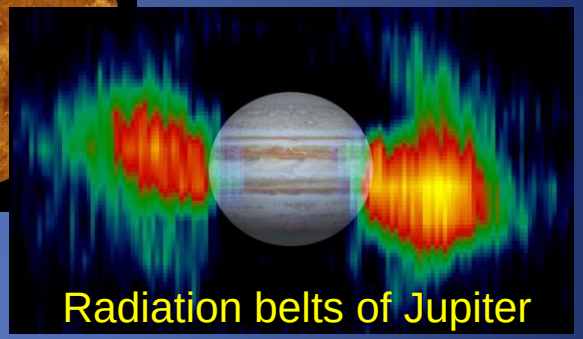
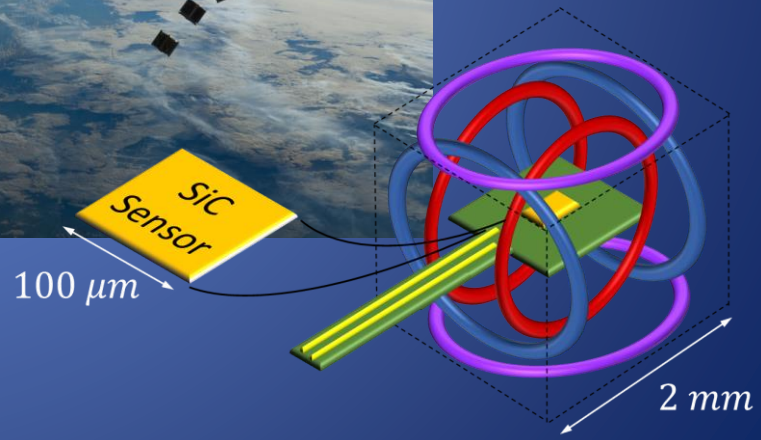



Image credit: NASA




- Future Work: Planetary Instrument Concepts for Advancement of Solar System Observations (PICASSO)
  - Model the observed response
  - Measure response from a few additional devices acquired from other laboratories
  - Trade geometry, size, doping, and processing of sensor for optimal field detection
  - Fabricate customized sensor with NASA Glenn Research Center

Miniaturization



# Questions?