Self-calibrating solid-state SiC magnetometer for planetary field mapping C.J. Cochrane*, J. Blacksberg, [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, *Corey.J.Cochrane@jpl.nasa.gov

Overview: We report on the initial stages of development of a new solid-state SiC magnetometer (SiCMag) intended for planetary field mapping. SiCMag measures magnetic field induced changes in spin dependent recombination (SDR) current within a SiC pn junction [1]. This change in SDR current arises from the interaction of external magnetic fields with the atomic scale defects intrinsic to the SiC semiconductor [2]. Although SiCMag, in its present form, is characterized as having a sensitivity of 440 nT/Hz$^{1/2}$, a custom sensor will be designed in the near future which will achieve a sensitivity below the 1 nT/Hz$^{1/2}$ limit.

Introduction: It's commonly known that fluxgate and optically pumped atomic gas based magnetometers are the instruments of choice because of their proven performance, reliability, and ability to adhere to the strict requirements associated with space missions. However, their complexity, size, and cost prevent their applicability in smaller missions involving cubesats. Conventional solid-state based magnetometers pose a viable solution, though many are prone to radiation damage and plagued with temperature instabilities. In this work, we report on the development of a new self-calibrating, solid-state based magnetometer based on a SiC pn junction. Unlike heritage designs, the magnetometer does not require inductive sensing elements, high frequency radio, and/or optical circuitry and can be made significantly more compact and lightweight. Additionally, the robustness of the SiC semiconductor allows for operation in extreme conditions such as the hot Venusian surface and the high radiation environment of the Jovian system. These features enable a variety of magnetic field sensing applications, including planetary entry probes, landers, and swarms of small picosats capable of science returns not possible with a single large-scale satellite. Our large scale prototype and planned coil system are illustrated in fig. 1.

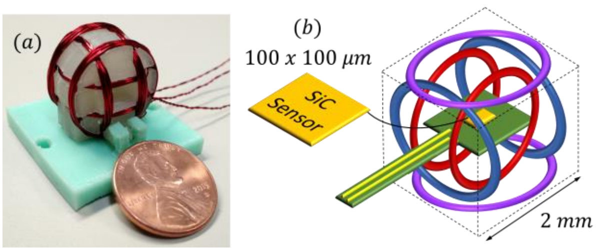

Figure 1: (a) Current "large scale" prototype and (b) planned coil system which will house the SiC sensor.

Operation: SiCMag is based on a magnetic field cancellation scheme that maximizes the SDR current in a SiC pn junction by maintaining a local region of zero-magnetic field across the volume of the device. The device is housed within three sets of Helmholtz coils (one for each dimension) that are driven independently to provide a low-frequency (<10Hz) cancellation field and a modulation field at audio frequencies. As the low-frequency driving current in these Helmholtz coils is directly proportional to the magnetic field it generates, its measure will serve as an indirect measure of the field being cancelled in each dimension.

Self-calibration: By measuring the electron nuclear hyperfine interactions that are observed in the higher

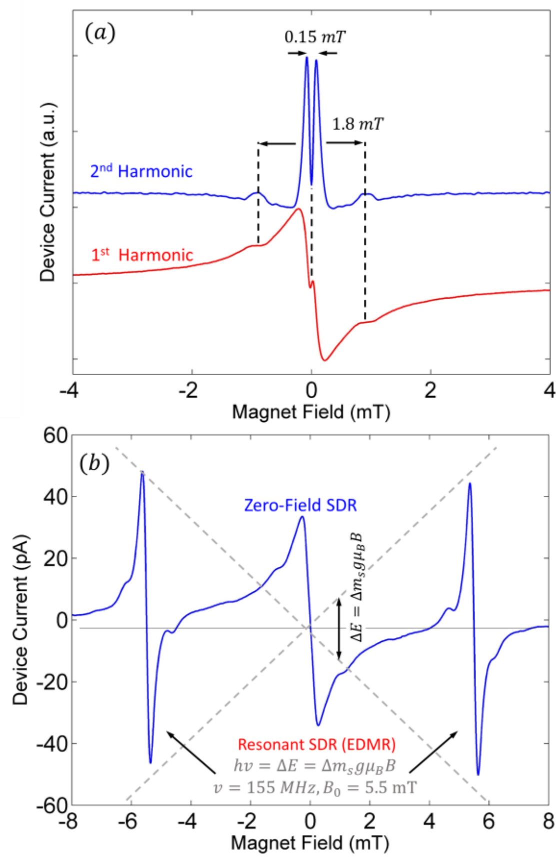

Figure 2: Self-calibration modes of SiCMag. (a) Well defined and stable electron nuclear hyperfine interactions observed in the higher order harmonic SDR responses can be used to self-calibrate the magnetometer. (b) EDMR measurement provides an absolute and redundant field measurement.

order harmonic SDR responses as illustrated in fig. 2a, SiCMag can leverage their stable magnetic field spacing to self-calibrate the magnetometer. Additionally, at the cost of adding a low radio frequency source and coil for offset field, one can leverage the electrically detected magnetic resonance (EDMR) response of the SiC defect electrons to provide an absolute and redundant magnetic field measurement as illustrated in fig 2b.

Sensitivity: Because the magnetometer relies on a magnetic field modulation scheme, the sensitivity of the instrument can be defined by the zero crossing slope of the response and the noise retained in the bandwidth of interest of the modulation frequency used. Figure 3a illustrates the measured sensitivity of the magnetometer at different biases applied to the SiC pn junction. As illustrated, the optimal sensitivity for this device is 440 nT/sqrt(Hz) when forward biased with 2.35 V. Figure 3b illustrates the magnetometer's response for three different axes (each offset by 1.5 pA for clarity) in the presence of an external, alternating axis, square wave magnetic field with amplitude of +/- 1500 nT. As illustrated in the figure, a frequency division multiplexing technique allows for simultaneous measurement of the x, y, and z magnetic field components. The signal-to-noise ratio of the data is consistent with the sensitivity metric depicted in fig. 3a

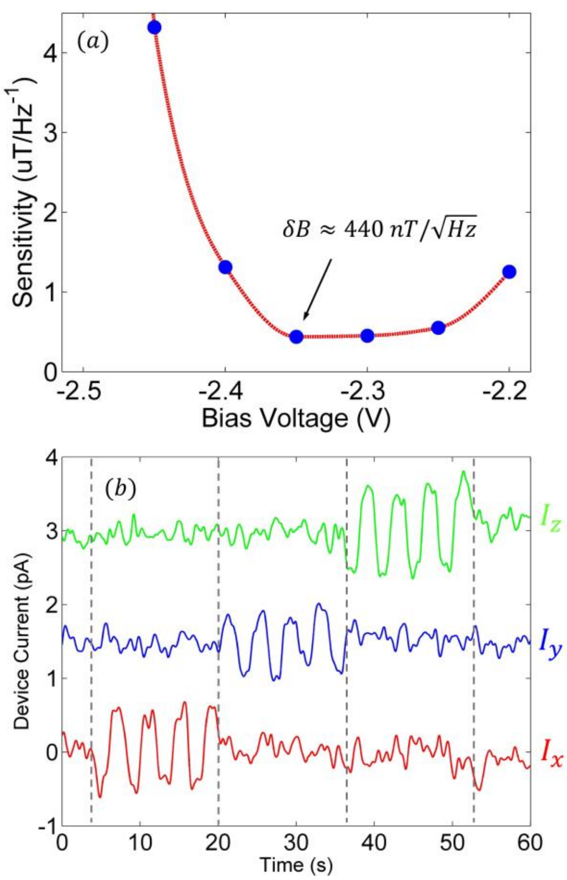

Figure 3: (a) Measured sensitivity of the magnetometer for a range of applied junction biases using a non-optimal SiC device. (b) Measurement of three current components versus time, each offset by 1.5 pA for clarity, in the presence of an alternating axis, ±1500 nT square wave magnetic field.

Applications for future NASA missions:

There are numerous relevant mission opportunities applicable for SiCMag, ranging from the large flagship missions to the smaller New Frontiers and Discovery missions. Because of the extremely small scale of the technology, it has significant potential for use on small spacecraft such as nanosats and picosats, where fluxgate and optically pumped sensors are too large for implementation. These small satellites can be used in swarms, thereby allowing for synchronous mapping of a planet's geomagnetic field without the need to make multiple orbits as required for large spacecraft. Additionally, if used on larger spacecraft, SiCMag's size and simplicity allows for multiple sensors to be placed around the spacecraft which would provide redundancy and inter-sensor calibration, allow for cancelation of stray fields from the satellite payload, make differential measurements for gradiometric science needs, and also allow for simultaneous measurements of magnetic fields at different frequencies. The collection of this information would make it significantly easier to distinguish between magnetic fields generated by internal dynamos, crustal magnetic fields, induced magnetic fields, and the interplanetary magnetic fields carried by the solar wind.

References: [1] C.J. Cochrane *et. al.* (2015) *Mat. Sci. Forum., Proc. 16th ICSCRM*, 858, 265-268. [2] C.J. Cochrane *et. al.* (2012) *J. Appl. Phys*., 112, 123714. [3] H. Kraus *et. al.* (2014) Nature Sci. Reps, 4, 5303. [4] D. Simin *et. al.* (2015) *Phys. Rev. Appl*., 4, 014009. [5] S.-Y. Lee *et. al.* (2015) Phys. Rev. B, 92, 115201.

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