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Simultaneous Magnetic Field and Temperature Measurements on a Battery with a Fiber-Coupled Quantum Sensor

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Summary: This work describes a proof-of-principle for simultaneous measurements of the temperature and current of a battery with the use of a single fiber-coupled nitrogen-vacancy-based sensor. These parameters can be used to obtain information about the State of Health of a battery device. Tracking the State of Health is important for maximizing the life cycle of a battery, and also for monitoring its safety.

Keywords: Quantum sensor, nitrogen vacancy centers, temperature sensor, magnetic field sensor, batteries

Background, Motivation and Objective

Long-lasting and reliable battery devices are a requirement for various applications in electric mobility as well as stationary energy storage. For such applications, it is important to monitor the battery's State of Health (SoH), which gauges the degradation of a battery over time. A deteriorated SoH can be observed empirically by measuring physical parameters of the battery such as the temperature and localized currents [1]. Monitoring the SoH is not only important for maximizing the duration of a device's life-cycle, but also for ensuring the safety of the device. In this talk, we will report on the use of a fiber-coupled nitrogen-vacancy-center-based sensor to simultaneously measure the magnetic field and temperature of different types of batteries. By leveraging the unique properties of nitrogen-vacancy (NV) centers, we aim to enhance the precision and reliability of battery monitoring systems.

Description of the New Method or System

The basic elements of the sensor are shown in the schematic in figure 1. The main element of the NV sensor is a 3x3x0.5 mm^3 diamond, with a NV-concetration of 4.5 ppm, glued onto the ferrule of an optical fiber. Wrapped around the ferrule is a copper coil that acts as an antenna for microwave driving of the NV centers. A 515 nm laser is used for optical excitation and a splitter is used to split of 1% of the green light. The light from the 1% arm of the splitter is attenuated and led unto the other arm of the balanced photo-detector. The remaining 99% proceeds to a circulator, after which it is sent to the diamond-containing fiber. The red light emitted from the diamond is collected by the same fiber and enters back into the circulator. Thereafter, excess green light is filtered out and red fluorescence is guided to one of the ports of a balanced photo-detector.

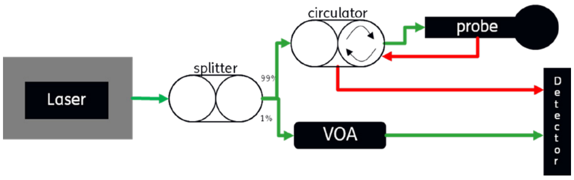

Fig. 1: Schematic of the optical elements of the sensor. The probe consists of an NV-containing diamond glued to an optical fiber. A copper wire is wound around the ferrule of this fiber for microwave driving of the NV-centers.

A continuous-wave optically detected magnetic resonance (CW-ODMR) measurement consists of the continuous application of green laser light and microwaves of varying frequency. Firstly, both are turned on for a set duration (typically 10-30 seconds) in order to let the system (temperature) stabilize. Next, the microwave frequency is increased periodically, and the fluorescence light intensity is recorded. In the resulting spectrum, eight resonances can be observed. Since the NV electron-spin ground state is spin-1, two transitions can be driven directly with microwaves ($m_s = 0$ to $m_s = -1$ and $m_s = 0$ to $m_s = +1$). Due to four possible orientations of the NV center in the diamond lattice, we then observe a total of eight transitions. Note that it is necessary to observe multiple NV orientations in order to extract the magnetic field vector (three variables) and the temperature (one additional variable) [2][3].

Measurements and Results

We start by calibrating the sensor for temperature. We use an external heater to control the diamond temperature and use a thermocouple to measure its temperature. For varying temperatures, we then measure the zero-field splitting ($\mathbf{D}$). We obtain a relation of $\mathbf{D}\left(\mathbf{T}\right) = 2.8728 *$

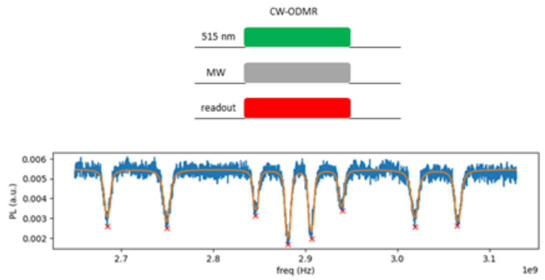

Fig. 2: (top) Measurement sequence to perform a continuous-wave optically detected magnetic resonance (CW-ODMR) measurement. The green laser and microwaves are turned on simultaneously and the resulting counts are recorded. (bottom) Photoluminescence (PL) plotted against the applied microwave frequency plotted in blue, the Lorentzian fit in orange, and red indicates the initial guesses for the fit.

$10^9 - 6.55 * 10^4 * \mathbf{T} - 162.0 * \mathbf{T}^2$, where $\mathbf{T}$ is the temperature of the diamond in degrees Celsius and $\mathbf{T}$ is the zero-field splitting in Hz.

Current and temperature measurements were performed on different batteries with different geometries and capacities: a pouch cell with a capacity of 3150 mAh, a cylindrical cell with a 2400 mAh capacity, and a coin cell of 200 mAh capacity. For the pouch cell, measurements were taken with the probe at different locations. Figure 3 shows the results of the two measurements on the pouch cell. A clear correlation between the measured magnetic field magnitude and the current in the battery can be observed.

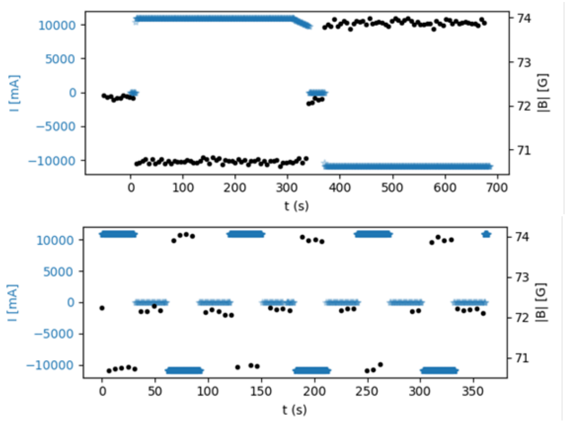

Fig. 3: Results for two measurements on the pouch cell. In the top image, the battery was charging for 5 minutes, followed by 30 seconds of resting, and 5 minutes of discharging. In the bottom image, the battery was cycled through 30 seconds of charging, resting, discharging, resting. For both measurements, the charging C-rate was 3.5C. The blue data points indicate the current that is running through the battery, and the black data points denote the magnetic field magnitude picked up by the NV sensor.

A clear distinction between measurements at the different locations on the pouch cell can be observed. On the contact of the battery, the magnitude of the changes in the measured magnetic field were almost a factor 10 bigger than on the center of the pouch cell. At the edge of the battery measured values were about 5 times bigger than at the center. For the measurements on the pouch cell, the temperature changes on the outside were not significant enough to be measured. In order to show the capability of our sensor to measure temperature, we additionally perform measurements on a cylindrical cell (Fig. 4).

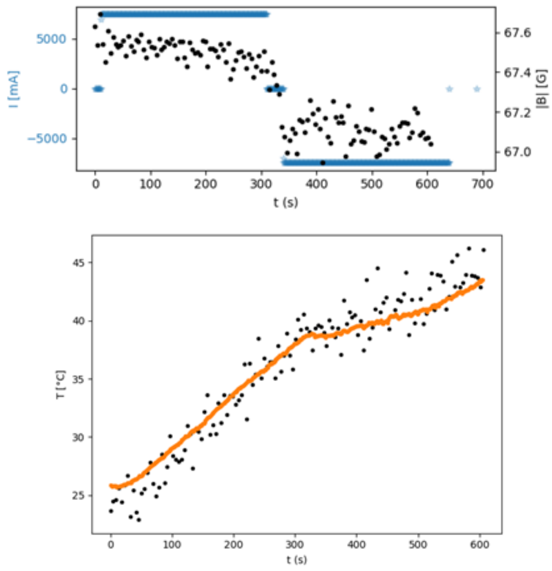

Fig. 4: Magnetic field (top) and temperature (bottom) data for a measurement on the cylindrical cell. (top) The blue points indicate the current on the battery, while the black points denote the measured magnetic field. (bottom) The orange data points indicate the temperature measured by the thermocouple and the black data points are the temperature as determined by the NV sensor.

Outlook

We showed proof-of-principle measurements for simultaneously measuring the temperature and current on the surface of a set of batteries with a fiber-coupled nitrogen-vacancy-center-based sensor. A next step is to perform such measurements on battery devices with different SoHs to determine how the physical parameters of the battery reflect the SoH. Eventually, the sensor could be used as a continuous monitor of the SoH of an arbitrary battery device.

References

[1] S. K. Pradhan and B. Chakraborty, “Battery management strategies: An essential review for battery state of health monitoring techniques,” Journal of Energy Storage, vol. 51, p. 104427, Jul. 2022, doi: 10.1016/j.est.2022.104427.

[2] Doherty, Marcus W., et al. ”The nitrogen-vacancy colour centre in diamond.” Physics Reports 528.1: 1-45, jul. 2013, doi: 10.1016/j.physrep.2013.02.001

[3] Chipaux, Mayeul, et al. ”Magnetic imaging with an ensemble of nitrogen-vacancy centers in diamond.” The European Physical Journal D 69 1-10, mayy 2015 10.1140/epjd/e2015-60080-1