Technical Note

Current measurements with Qnami ProteusQ™

Release date: 28 March 2022

Scanning NV magnetometry unlocks the characterization of local currents with excellent spatial resolution. In this note, we discuss measurements of devices in working conditions using Qnami ProteusQ™ equipped with Vario PQ[1]. We show that it is possible to detect small DC currents. Furthermore, we reveal the magnetic field induced by the current in a micro-loop and characterize its spatial homogeneity.

Devices are characterized in working conditions when external currents or voltages are applied. This allows, for example, the examination of a chip for failure analysis purposes, the observation of current flow in 2D materials or microwave-imaging in RF resonators. We apply a current to the sample using Vario PQ (showed in Fig. 1a). The current flows through a nanostructure and induces a local magnetic field. We detect this field using the optically detected magnetic resonance (ODMR) of a single NV center [2]. ODMR requires the application and read-out of laser light through an optical system (the objective is seen in Fig. 1a, top) while a microwave frequency is applied via an antenna (Fig. 1a, right). The laser excites a single NV center which is implanted in a scanning probe tip, the Quantilever™ MX (mounted from the left in Fig. 1a).

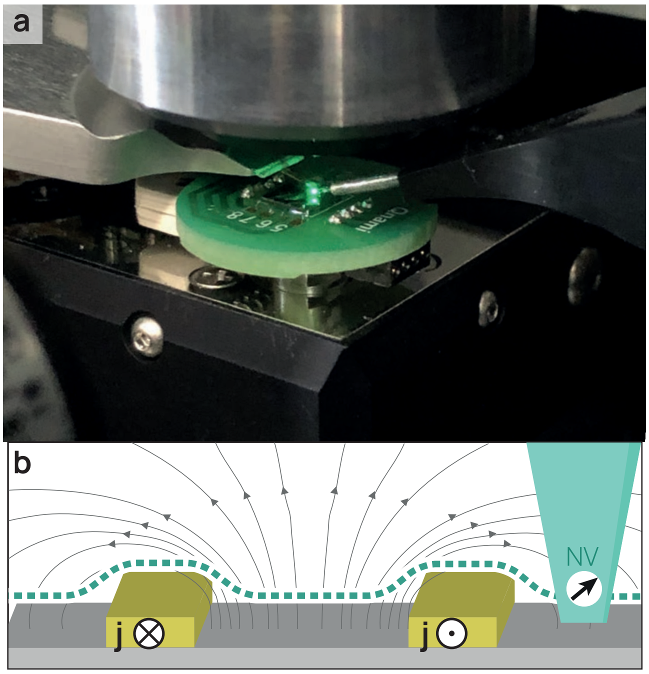

Fig. 1: Measurements in working conditions: a) Qnami ProteusQ™ equipped with Vario PQ. b) A current density j passing through a wire (yellow) induces a magnetic stray field pattern (gray lines). The local magnetic field as well as the topography (dashed line) is detected with a scanning NV tip.

An illustration of the magnetic stray field generated by two parallel wires is sketched in Fig. 1b, relating to the measurements that we discuss later. A current is passed in opposite direction through the wires. The magnetic field between the wires points perpendicular to the plane. During the measurement, the Quantilever™ MX records simultaneously the topography (dashed line) and the magnetic field B_{NV}[1]. From B_{NV} the local current density can be readily calculated.

[1] B_{NV} is the projection of the local magnetic field vector along the NV quantization axis, at a height corresponding to the implantation depth of the NV center.

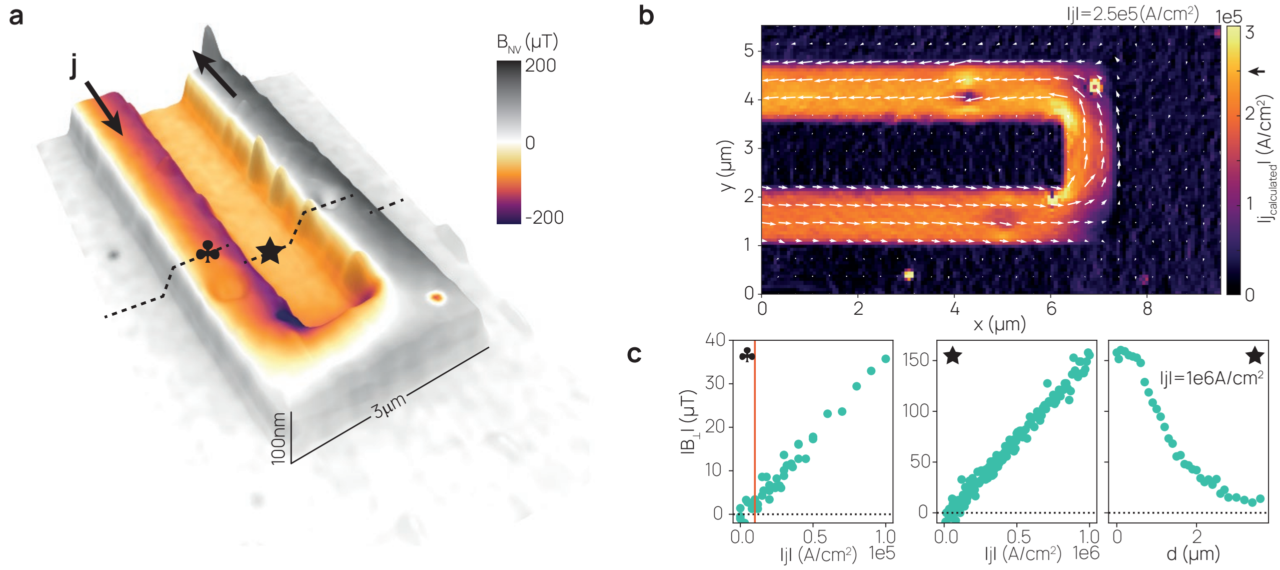

Fig. 2: Characterization of devices in working conditions: a) A current $I = 250\,\mu\text{A}$ ($|\mathbf{j}| = 2.5 \times 10^5\ \text{A/cm}^2$) is applied to a Cr/Au (10/90 nm) loop. The plot shows the measured topography and surface magnetic field $B_{\text{NV}}(x, y)$. b) Calculated local current density $|\mathbf{j}_{\text{calculated}}|\,(x, y)$ from the data in (a). Vectors depict the spatial components of $|\mathbf{j}|$. c) Perpendicular component of the magnetic field $B_\perp(|\mathbf{j}|, d = 0)$ at position ♣ (left) and ★ (middle) and $B_\perp(d, |\mathbf{j}| = 1 \times 10^6\ \text{A/cm}^2)$ at position ★ (right).

In Fig. 2a we show the results of measurements in working conditions of a 100 nm thick Cr/Au wire. A current of $250\,\mu\text{A}$ is applied, corresponding to a current density of $|\mathbf{j}| = 2.5 \times 10^5\ \text{A/cm}^2$. B_{NV} is plotted as surface color on the measured topography. We detect a rather homogeneous magnetic field inside the loop.

We then use the data to calculate the local current density $|\mathbf{j}|$. The magnetic field and the current density are related by the Biot-Savart law. In Fourier space, one obtains:

$$\mathcal{J}_x = \frac{\alpha k_y}{-u_x k_y - u_y k_y + i u_z k}\mathcal{B}_{\theta,\phi}$$

$$\mathcal{J}_y = \frac{\alpha k_x}{u_x k_x + u_y k_y - i u_z k}\mathcal{B}_{\theta,\phi}$$

Here, $\mathcal{J}_x$ ($\mathcal{J}_y$) is the Fourier transform of the current density in x- (y-) direction, $\mathcal{B}_{\theta,\phi}$ is the Fourier transform of the magnetic field measured along the NV direction given by the spherical angles θ and ϕ, k_x, k_y are the Fourier-space vector variables with $k = \sqrt{k_x^2 + k_y^2}$, the parameter $\alpha = 2e^{kd}/\mu_0$ includes the scanning height d and the vacuum permeability μ_0, and $u_x = \sin(\theta)\cos(\phi)$, $u_y = \sin(\theta)\sin(\phi)$. For the calculation we need to make assumptions on the scan height d and the orientation θ, ϕ of the NV center. For the scan height we take a typical value of $d = 25\,\text{nm}$, the angle $\phi = 45°$ is given by the crystallographic orientation of a 100 tip, and we take $\theta = 80°$. For details on calculating the current see Ref.[3].

The result of the calculation is shown in Fig. 2b. The arrows depict the calculated x- and y-component of $\mathbf{j}$. Beside the sanity check that the current actually flows in the wire and that we recover the applied magnitude for $|\mathbf{j}|$ (indicated with an arrow on the color bar), two interesting details are observed. First, some but not all defects in the wire lead to an enhanced current flow in their vicinity and second, the current flow is enhanced in the inner edges of the U-shape and reduced at the outer edges.

Finally, in Fig. 2c (left panel) we place the Quantilever™ MX on the loop and vary the applied current density $\mathbf{j}$. This allows to extract a typical value of DC current densities that are measurable in this setup, amounting to $|\mathbf{j}| = 1 \times 10^4\ \text{A/cm}^2$ (indicated by the orange line). We repeat the measurement inside the loop and vary $|\mathbf{j}|$ (middle panel) and the distance to the plane (right panel). Also in the loop, the magnetic field increases linearly with applied current, as expected. We measure a perpendicular field $B_\perp = 160\,\mu\text{T}$ when applying a current of 1 mA ($|\mathbf{j}| = 1 \times 10^6$ A/cm^2). The trace shows that we can safely resolve magnetic fields down to 10 µT. Furthermore, a current density of $|\mathbf{j}| = 1 \times 10^6$ A/cm^2 is still detectable in a height $> 2\,\mu$m.

The Qnami ProteusQ™ setup is well suited to:

- In-situ apply a current or a voltage (Measurements in working conditions)
- Detect the spatial inhomogeneity of B, induced by a current-carrying nanostructure
- Measure small local current densities of $|\mathbf{j}| = 1 \times 10^4$ A/cm^2

Further reading

- Qnami technote on measuring magnetic field with NV centers [2]
- Qnami whitepaper about NV magnetometry [4]

References

[1] Qnami AG, *Vario PQ characterize devices in working conditions*, (2022) https://qnami.ch/wp-content/uploads/2022/03/VarioPQ_Brochure.pdf.

[2] Qnami AG, *Fundamentals of magnetic field measurement with NV centers in diamond*, (2020) https://qnami.ch/wp-content/uploads/2020/12/2020-12-07-Qnami-TN1-The-NV-center-1.pdf.

[3] D. Broadway, S. Lillie, et al., "Improved current density and magnetization reconstruction through vector magnetic field measurements", Phys. Rev. Applied **14**, 024076 (2020).

[4] Qnami AG, *NV Magnetometry*, (2020) https://qnami.ch/wp-content/uploads/2020/07/Qnami_WhitePaper1_NV_magnetometry-5.pdf.

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