Technical Note

Spatial resolution in Scanning NV Magnetometry

Related products: Qnami ProteusQ™, Quantilever™MX

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At one glance

The present technical note explains how spatial resolution is defined in Scanning NV Magnetometry. For a given distance d between the NV center and the scanned surface, the best achievable lateral spatial resolution is $0.86\,d$.

1 Theoretical spatial resolution in scanning NV magnetometry

Spatial resolution of any imaging technique characterizes the power to resolve nearby objects in real-space. In optics, spatial resolution is set by Abbe's famous diffraction limit. In scanning probe microscopy, resolution is generally less straightforward to define, as it may be influenced by many, sometimes hard-to-determine quantities, such as tip geometries, tip-sample distance, electric or magnetic properties of the scanning probe etc.

For scanning NV magnetometry (SNVM), however, the definition of spatial resolution is more straightforward, because the size of the sensor (i.e. the extent of the NV's electronic wave function) is point-like for all practical purposes. In this situation, spatial resolution is determined by one quantity alone: The distance d between the scanning NV and the (two-dimensional) sample of interest. This fact is illustrated in Fig. 1, which shows the out-of-plane component B_z of the magnetic stray-field generated by two out-of-plane-oriented spins, located on a sample plane and laterally separated by a distance λ from each other. For $d \ll \lambda$ we observe two distinct peaks in B_z, which correspond

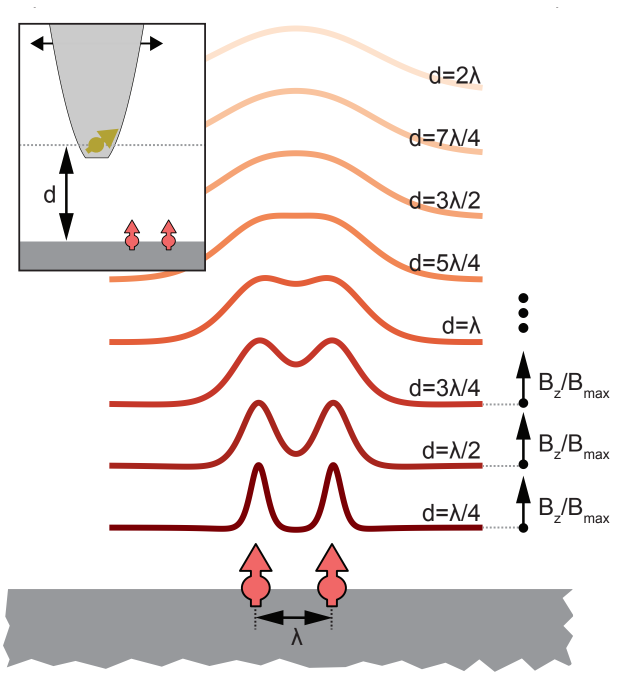

Fig. 1: Spatial resolution in scanning NV magnetometry
The out-of-plane component of the magnetic stray-field generated by two dipoles separated by a distance λ is plotted for different position of the NV center. When the distance d between the NV center and the surface exceeds $5\lambda/4$, the local stray-field minimum between both dipoles disappears preventing the identification of their individual positions.

to the stray-field generated by each spin. As d increases, the stray-field maxima become increasingly difficult to distinguish. Similar to a resolution criterion in optical imaging, one can then define the limit of spatial resolution as the point where the local minimum in B_z between the two dipoles disappears. One can numerically determine that this disappearance of the local minimum corresponds to the condition that $d \approx 1.16\lambda$. From this, one can then define a minimal resolution for a fixed scanning distance d of

$$\lambda_{\min} = 0.86d\,. \tag{1}$$

A more formal and generally applicable discussion of spatial resolution in scanning NV magnetometry is based on an analysis of the propagation of magnetic fields away from a sample surface, as described by Maxwell's equations. As extensively discussed in literature [1–3], such propagation is conveniently performed in the Fourier space, where it is found that the amplitude of any given Fourier component of the magnetic field with in-plane wave vector $\mathbf{k}$ decays with distance z from the sample surface as $\propto e^{-|\mathbf{k}|\cdot z}$. This exponential suppression of Fourier components with increasing wave-vector $\mathbf{k}$ highlights again the fact that the NV-sample distance d is key and the sole quantity which determines spatial resolution in scanning NV magnetic imaging of DC fields.

We note that the analysis of spatial resolution is less straightforward if a sample cannot be considered to be purely two-dimensional (i.e. if the effective sample thickness exceeds d) or even for two-dimensional samples with non-uniaxial spin textures. An illustrative example for the difficulties that can arise in this case is given by so called "flux-closure states", which are magnetic textures that generate no stray magnetic fields. The existence of flux-closure states illustrates the fact that reverse propagation from stray magnetic fields to the underlying source in the most general case is an ill-posed problem which has no unique solution. Still, by making reasonable assumptions about spin textures, useful information can be extracted from NV-based stray-field imaging in most practical cases. For a more in-depth discussion of reverse propagation and image analysis for NV magnetometry, we refer the reader to recent literature in the field [2, 3].

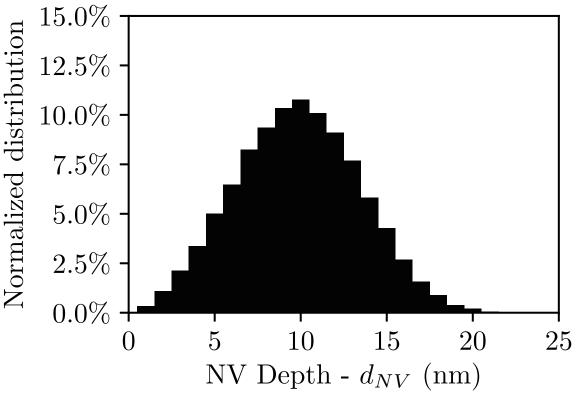

Fig. 2: Theoretical NV depth profile corresponding an implantation energy of 6 keV
The Nitrogen depth profile is obtained using SRIM simulation (http://www.srim.org/). For an implantation energy of 6 keV the simulation predicts an average depth of 9.4 ± 3.6 nm. An experimental determination of the exact relationship between depth-distribution and ion implantation energy is a matter of ongoing research.

2 Spatial resolution and NV implantation depth

The NV-sample distance d in scanning NV magnetometry is set by two contributions, $d = d_{\mathrm{NV}} + d_{\mathrm{tip}}$, where d_{NV} is the distance of the NV from the tip of the diamond scanning probe and d_{tip} is the distance between the tip and the sample. The two quantities are determined by entirely different factors.

On the one hand, d_{tip} is affected by AFM feedback parameters, by possible sample contamination or sample "dead layers" and by hard-to-avoid water-layers on the surface. On the other hand, d_{NV} is a property of the diamond scanning probe alone and therefore determined during the fabrication process of the probe.

The NV centres in QuantileverMX scanning probes are created by a sophisticated process of ion-implantation and sample annealing. The energy at which Nitrogen ions are implanted into the diamond during fabrication then sets d_{NV}, up to an uncertainty originating from "ion straggling", i.e. unavoidable, stochastic variations in the ion penetration range. This implantation energy is a key specification, well-defined for all of our QuantileverMX devices.

Figure 2 shows a theoretical estimate of the depth profile of Nitrogen atoms implanted into diamond at an energy of 6 keV. The simulation was performed using the freely available software package "SRIM", which makes the key simplification of assuming implantation into an amorphous, i.e. non-crystalline target. This approach thus neglects effects such as "ion chanelling", which result from the crystalline nature of the diamond and generally result in a larger implantation depth than predicted by SRIM. The distribution shown in Fig. 2 should therefore be considered a lower-bound estimate for the actual NV depth distribution resulting from 6 keV Nitrogen ion implantation. A determination of the exact relationship between depth-distribution and ion implantation energy for single crystal diamond material is a matter of ongoing research [4].

References

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