# Laser Modulation of Superconductivity in a Cryogenic Wide-field Nitrogen-Vacancy Microscope

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resolution, providing a new platform for spatially resolved investigations of a range of systems from topological insulators to van der Waals ferromagnets.

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itrogen-vacancy (NV) center microscopy<sup>1,2</sup> is a multimodal imaging platform increasingly used to interrogate biological<sup>3</sup> and condensed matter systems<sup>4</sup> at room temperature, where the long coherence times of the NV spin state enable high sensitivities in ambient conditions.<sup>5,6</sup> Recent experimental efforts have extended NV microscopy to cryogenic temperatures<sup>7-9</sup> at which it can been used to investigate low-temperature phenomena such as transport and magnetism in low-dimensional systems.<sup>10,11</sup> Superconductivity is one such phenomenon to which NV microscopy is particularly applicable.<sup>12,13</sup> Previous studies have mainly focused on high- $T_c$  superconductors, probing the Meissner effect with ensembles of NV centers<sup>14-18</sup> and achieving nanoscale imaging of microstructures and Abrikosov vortices using scanning single NV experiments.<sup>8,9,19</sup> Vortices in a high-T<sub>c</sub> superconductor have also been imaged using wide-field imaging of NV ensembles.<sup>20</sup>

However, the viability of NV microscopy for more temperature-sensitive systems, such as superconductors with a  $T_c \leq 10$  K or electronic systems in the ballistic regime, remains to be seen. Indeed, at low temperatures the "non-invasiveness" of the NV imaging platform becomes questionable, given the appreciable laser intensity impinging on the sample (up to ~1 mW/ $\mu$ m<sup>2</sup>, corresponding to saturation of the NV optical cycling) and microwave power (up to mWs)

necessary to initialize, manipulate, and read out the NV spin state. Application of these fields can cause undesirable heating of the sample of interest and hence potentially affect the imaged phenomenon. Wide-field imaging has many advantages over scanning single NV imaging, namely the ability to rapidly interrogate structures over large (tens to hundreds of micrometers) fields of view<sup>21,22</sup> and perform multimodal measurements simultaneously;<sup>23–25</sup> however, it presents additional challenges owing to the correspondingly large illumination area requiring total laser powers of up to hundreds of milliwatts. Such powers are much larger than the typical cooling power provided by a helium bath or closed-cycle cryostats at a base temperature of 4 K, casting doubt on the possibility to operate at this temperature.

In this work, the impact of these essential components of NV microscopy is assessed by imaging superconducting niobium (Nb) devices in a cryostat with a base temperature ( $\sim$ 4 K) close to its critical temperature ( $T_c \approx 9$  K). Superconducting phenomena, namely the nucleation of

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Abrikosov vortices,<sup>26</sup> are used to assess the local heating from the excitation laser. We use electrical resistance measurements to quantify heating along the conduction path across the film and compare to the insight from local imaging. Additionally, we image transport currents within a Nb device in both fully superconducting and normal states and observe a nonuniform current distribution in the superconducting case which we associate with the nonuniform temperature profile due to the laser. This work has implications for future low-temperature imaging experiments using NV microscopy in both wide-field and confocal configurations, identifying a regime of laser power conditions for which operation at sample temperature approaching 4 K is possible. Under these minimally invasive conditions, the wide-field NV microscope demonstrated here is an appealing tool for condensed matter studies, which may enable real-space investigations of a range of phenomena such as transport in topological insulators or in low-dimensional electronic systems, magnetization dynamics in van der Waals ferromagnets and heterostructures, and superconductivity in 2D materials, to name just a few.

The cryogenic wide-field NV microscope used for this study houses the sample in a closed-cycle cryostat with a base temperature down to 4.0 K (see details in SI, Section III), equipped with a superconducting vector magnet allowing application of a uniform magnetic field up to 1 T along an arbitrary axis,  $B_{app}$ . The cryostat contains a cage-mounted optics column which includes a high numerical aperture objective lens and is accessible via a window at the top of the cryostat (Figure 1a). A 532 nm laser is used to initialize and readout the NV-spin ensemble, and the red photoluminescence (PL)  $(650-800 \text{ nm})^{27}$  is collected via the same optics column and focused onto an sCMOS camera (Figure 1a). The NV-diamond used in these experiments is a 50  $\mu$ m thick membrane irradiated to form an NV imaging layer extending 200 nm below the diamond surface (see SI, Section I).

Four 200 nm thick Nb devices were fabricated directly on the diamond surface, each device featuring two square bonding pads (200  $\mu$ m) connected by a narrow channel (200  $\mu$ m × 40  $\mu$ m) (Figure 1b) (see SI, Section II). The diamond was mounted to a glass coverslip featuring an omega-shaped microwave resonator for NV spin-state driving, which itself was mounted to a printed circuit board (PCB) for electrical contact to the resonator and Nb devices. This PCB was mounted to a stage equipped with a thermistor and heater for control and measurement of the near-sample temperature. Imaging of the near surface NV-layer occurs through the coverslip and bulk of the diamond with the devices on the underside of the sample (Figure 1c).

Prior to imaging, the devices were characterized electrically to identify their critical temperature. The resistance across each device (*R*) was measured as a function of temperature as read by the thermistor on the sample holder,  $T_{sensor}$  (see SI, Section IV). All devices showed a superconducting transition at a critical temperature  $T_c \approx 9 \text{ K}$ , where, for example, *R* decreases from the normal-state resistance,  $R_N = 50.2 \Omega$ , to the superconducting resistance,  $R_{SC} = 34.6 \Omega$ , which corresponds to the resistance of the nonsuperconducting leads (Figure 1d). A typical PL image of the NV-layer beneath the Nb film under continuous wave (CW) illumination shows the Gaussian beam profile with a 43  $\mu$ m beam waist giving reasonable illumination across a 100  $\mu$ m field of view (Figure 1e). At a total laser power of  $P_{\text{laser}} = 1.0 \text{ mW}$ , we note that imaging the sample



**Figure 1.** A cryogenic wide-field nitrogen-vacancy microscope. (a) Schematic of the cryogenic wide-field NV microscope (see description in text). (b) Photograph of thin-film Nb devices fabricated on the NV-diamond surface. The diamond is mounted to a coverslip with a microwave resonator visible beneath the diamond. (c) Schematic of the sample mount (see description in text). (d) R versus  $T_{\text{sensor}}$  for a single Nb device. The resistance drops from the normal-state resistance,  $R_{\text{N}}$ , to the superconducting resistance,  $R_{\text{SC}}$ , and is characterized by temperatures  $T_+$  and  $T_-$  which differ from  $R_{\text{N}}$  and  $R_{\text{SC}}$  by  $\Delta R = 0.05 \times (R_{\text{N}} - R_{\text{SC}})$  respectively. (e) NV-layer PL image demonstrating the 100  $\mu$ m field of view, taken under continuous wave (CW) laser illumination at  $P_{\text{laser}} = 1.0$  mW. Coordinate system used for all subsequent measurements is defined.

results in only a slight change of the temperature as measured by the thermistor  $\Delta T_{\rm sensor}$  = 0.05 K.

We now move to NV magnetic imaging of a Nb device, focusing initially on vortices in the large Nb pad under no applied current. The sample was cooled to  $T_{\text{sensor}}$  = 4.3 K under a uniform magnetic field perpendicular to the film plane (zaxis),  $B_{app} = 1.5$  G, with the laser off. The net magnetic field was imaged using CW optically detected magnetic resonance (ODMR) at a range of laser powers. Images of the magnetic field in the z-direction,  $B_{z}$ , reconstructed from the NV ODMR (see SI, Section VI) are presented in Figure 2a–d. At  $P_{\text{laser}} =$ 0.5 mW, the  $B_z$  image shows vortices distributed across the field of view (Figure 2a) with a number density that is consistent with the theoretical value for such films,  $n = B_{app}/$  $\Phi_0$ , where  $\Phi_0$  is the magnetic flux quantum<sup>28</sup> (see SI, Figure S7). At  $P_{\text{laser}} = 1.0 \text{ mW}$ , vortices disappear from pockets near the center of the image, whereas those toward the edge remain fixed (Figure 2b). At  $P_{\text{laser}} = 2.0$  and 4.0 mW, we see a disc centered on the laser spot in which the vortices are removed whereas again the vortices toward the very edge remain fixed



**Figure 2.** Laser heating of Abrikosov vortices. (a–d)  $B_z$  images of vortices measured by ODMR at  $P_{\text{laser}} = 0.5$ , 1.0, 2.0, and 4.0 mW, respectively. The location of the imaged region is on the contact pad of the Nb device as indicated in the inset of (a). The sample was cooled to base temperature ( $T_{\text{sensor}} = 4.3 \text{ K}$ ) with the laser off at a field  $B_{\text{app}} = 1.5 \text{ G}$  and imaged at the same field. A background subtraction algorithm was applied to remove features varying over 20 pixel length scales or greater, which we attribute to artifacts in the frequency fitting at reduced contrast at low fields (see SI, Section VI). (e–h) Maps of the PL contrast of a single resonance line in the ODMR measurement used to reconstruct the  $B_z$  images in (a–d). The reduced contrast near sites of vortex suppression indicates local reduction in the MW field strength (see SI, Section IX). (i) Illustration of laser heating of the Nb film at increasing  $P_{\text{laser}}$ , which is at base temperature when the laser is off. A temperature profile is imprinted on the Nb film by the laser but remains below  $T_c$  ( $P_{\text{laser}} = 0.5 \text{ mW}$ ). Increasing  $P_{\text{laser}}$  gives a large area of normal-state Nb where the laser is most intense, removing the vortices ( $P_{\text{laser}} = 1.0 \text{ mW}$ ). Further increasing  $P_{\text{laser}}$  gives a large area of normal-state Nb centered on the laser spot ( $P_{\text{laser}} = 2.0 \text{ mW}$ ). (j) PL image highlighting the local variations in the laser beam profile across the Nb film. Broader variations in the PL (varying over length scales 20 pixels or larger) have been subtracted to emphasize deviations from the approximately Gaussian profile. (k,l)  $B_z$  images showing vortex clustering around hot spots when the laser power is reduced to  $P_{\text{laser}} = 0.5 \text{ mW}$  after imaging at  $P_{\text{laser}} = 2.0 \text{ mW}$  and  $P_{\text{laser}} = 4.0 \text{ mW}$ , respectively. All scale bars are 20  $\mu$ m.

(Figure 2c,d). Comparing the  $B_z$  images with ODMR contrast maps from the same measurements (Figure 2e–h), we observe that the regions where the vortices are removed correlate with regions in which the contrast is reduced, indicating a local reduction in the MW field strength as confirmed by independent Rabi measurements (see SI, Section IX).

These observations can be explained by local laser heating of the Nb film raising the temperature of some regions within the field of view above  $T_c$  (Figure 2i). Here, temperature refers to the lattice (phonon) temperature assuming an equilibrium quasiparticle density; however, diffusion of hot quasiparticles may also play a role in the system.<sup>29</sup> As  $P_{\text{laser}}$  is increased from 0.5 to 1.0 mW, pockets of normal-state Nb are formed where the local laser intensity is largest (and  $T > T_c$ ), thereby removing the vortices. These regions are highlighted by subtracting the broader Gaussian curve from a PL image (Figure 2j). Increasing  $P_{\text{laser}}$  further, these pockets merge to form a normal-state disc centered in the field of view. The attenuation in the MW field under the normal-state regions is ascribed to a different response compared with the surrounding superconducting film.<sup>30</sup> Although the exact mechanism remains unclear (see discussion in SI, Section IX), this observation illustrates how NV imaging may be used to investigate the ac response of complex superconducting structures, as recently demonstrated by Xu et al.<sup>18</sup>

Additionally, we observe clustering of vortices around intensity maxima in the laser profile when  $P_{\text{laser}}$  is reduced from powers giving large areas of normal-state Nb ( $P_{\text{laser}} = 2.0$  and 4.0 mW) to a less invasive power ( $P_{\text{laser}} = 0.5$  mW) (Figure 2k,l). This is because as the normal region shrinks, the vortices renucleate in the superconducting region where they are attracted by the nearest hot spot,<sup>31</sup> that is, near the normal/superconducting boundary. The vortices therefore cluster around local temperature maxima, where they are pinned once the Nb cools further (see SI, Section XI, for modeling and further discussion). A faster reduction in  $P_{\text{laser}}$  reduces this clustering effect (see SI, Figure S9). Moreover, uniform vortex configurations are recovered by heating the system globally

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Figure 3. Probing local laser heating with electrical measurements. (a)  $T_{\text{sensor}}$  versus  $P_{\text{laser}}$  with no additional heating, varying the location of the laser spot as identified on the inset diagram: 200  $\mu$ m from the Nb film (green), on the narrow Nb channel (purple), and on the center of the Nb bonding pad (orange). (b–d) R versus  $T_{\text{sensor}}$  for a single Nb device at increasing  $P_{\text{laser}}$  (light to dark) with the laser spot focused on (b) the diamond 200  $\mu$ m from the Nb film; (c) the middle of the Nb bonding pad; and (d) the narrow Nb channel. The resistance was measured with a 10  $\mu$ A current. (e)  $\Delta T_{\min}$  versus  $P_{\text{laser}}$  for the laser spot focused at the identified locations.  $\Delta T_{\min}$  is the magnitude of the shift in  $T_+$  from its value when the laser is off. (f)  $\Delta T_{\max}$  versus  $P_{\text{laser}}$  for the laser spot locations.  $\Delta T_{\max}$  is the magnitude of the shift in  $T_-$  from its value when the laser is off. (g) Schematic of two heating scenarios, one with laser focused on the bonding pad (upper) and the other with the laser focused on the center of the narrow channel (lower). The location of  $\Delta T_{\min}$  and  $\Delta T_{\max}$  are indicated in each case. (h) Illustrative plot of the temperature distribution along the path of least resistance across the device with (red) and without (blue) laser heating, showing the location of  $\Delta T_{\min}$  and  $\Delta T_{\max}$ .

above  $T_c$  and cooling in the absence of laser (see SI, Figure S9). Recently, thermal gradients arising from focused laser beams have achieved patterning at the single vortex level,<sup>32</sup> whereas ensembles of vortices can be manipulated by nanopatterned current profiles,<sup>33</sup> temperature patterning,<sup>34</sup> and local magnetic fields.<sup>35</sup>

The images presented demonstrate the invasiveness of widefield NV microscopy in this case. Imaging the Nb film with  $P_{\text{laser}} = 2.0 \text{ mW}$  gives a normal-state region nearly the size of the laser spot, indicating heating in this region upward of >5 K given the base temperature 4.3 K and the Nb  $T_c \approx$  9 K. Such a laser power corresponds to a relatively modest peak intensity of  $40 \text{ W/cm}^2$ , which is 4 orders of magnitude lower than the laser intensity needed to saturate the optical cycling of the NV,<sup>36</sup> as is often employed in single NV experiments. Surprisingly, the temperature at the sensor remains close to the base temperature in these measurements, with  $T_{sensor}$  < 4.4 K at  $P_{\text{laser}} = 2 \text{ mW}$ . A linear response of  $T_{\text{sensor}}$  to  $P_{\text{laser}}$  is observed (Figure 3a) with a slope that depends on the location of the laser beam: the thermistor is heated most efficiently when a greater portion of the laser is incident on the transparent diamond. In any case,  $T_{sensor}$  remains below 4.7 K for  $P_{\text{laser}}$  up to 10 mW, implying that there exist strong temperature gradients across the sample, which may be overlooked if local indicators are not available.

To further quantify the local heating, we measure the resistance, R, as a function of  $T_{\text{sensor}}$  (controlled by the heater) and  $P_{\text{laser}}$ , when the laser spot is focused at various locations around the device. When the laser is focused 200  $\mu$ m from the Nb film, the R versus  $T_{\text{sensor}}$  curves shift to lower  $T_{\text{sensor}}$  as  $P_{\text{laser}}$  increases, indicating a global heating of the Nb device (Figure 3b). When the laser spot is focused on the Nb bonding pad, the curves shift again, but the shape is severely distorted, as  $T_{-}$  moves to lower  $T_{\text{sensor}}$  at a faster rate than  $T_{+}$  as  $P_{\text{laser}}$  increases (Figure 3c,  $T_{\pm}$  defined in Figure 1d). This scenario is exacerbated when the laser is focused on the narrow channel,

where the full width of the current path is encompassed by the laser spot (Figure 3d).

The minimum and maximum temperature increase along the current path through the device  $(\Delta T_{\min} \text{ and } \Delta T_{\max})$  can be quantified by the shift in  $T_+$  and  $T_-$  at a given  $P_{\text{laser}}$  from their values when the laser is off (Figure 3e,f). In the case where the laser is focused on the narrow channel, where the current must pass through the maximally heated part of the device (Figure 3g lower), we find a maximum temperature increase of >2 K/mW, sufficient to completely quench the superconductivity of the illuminated section of the strip at  $P_{\text{laser}} = 2 \text{ mW}$ . This is consistent with Figure 2g where imaging at  $P_{\text{laser}} = 2.0 \text{ mW}$ results in a normal-state Nb disc centered on the laser spot  $\sim$ 50  $\mu$ m in diameter. The minimum temperature increase of ~0.5 K/mW suggests that the whole Nb device experiences significant heating even 1 mm away from the laser spot. This is possibly indicative of a relatively poor thermal conductivity of our implanted diamond substrate and/or a poor thermal contact with the Nb film. When the laser is focused on the bonding pad, the current avoids the hottest part of the device directly under the laser spot (Figure 3g upper), and so  $\Delta T_{\text{max}}$  is reduced and is closer to the global minimum heating of ~0.5 K/mW as compared to the previous case (Figure 3h). The heating of the Nb film is reduced but still measurable with the laser off of the Nb device ( $\sim$ 0.2 mm away),  $\sim$ 0.1 K/mW, just a factor of 3 shy of the heating measured at the sensor. Heating of the sample by the microwave field was also assessed and found to give a small global temperature change ( $\sim 0.1 \text{ K}$ ) across the device at powers relevant to most imaging applications (see SI, Section V).

Resistance measurements allow us to characterize local heating due to the laser and infer its impact on the current path; however, the impact of laser heating on the local current distribution can be imaged directly by measuring the Ørsted field using ODMR. Direct reconstruction of current paths in superconductors is of particular interest to superconducting (a) (b) (c) (g) Т 0 mW 200 B  $T_c$ 0 Ē 200 Laser of 400 Vertical line cut  $P_{\text{laser}} = 0.25 \text{ mW}$  $P_{\text{laser}} = 0.5 \text{ mW}$ P<sub>laser</sub> = 1.0 mW (d) (e) (f) (h) -700 700 -60 600 -50 500 **J** (A/m (M/m) -40 400 300 -20 200 100 40 60 80 100 Distance-y (µm)

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**Figure 4.** Laser heating of superconducting transport. (a–c) Images of the magnetic field in the *z*-direction due to charge transport within the Nb channel, imaged at  $P_{\text{laser}} = 0.25$ , 0.5, and 1.0 mW. The background field that facilitates the measurement has been subtracted. (d–f) Total current density map reconstructed from the accompanying  $B_z$  images (see SI, Section XII, for reconstruction details). A total current of 20 mA was maintained throughout the acquisition of these images. The device resistance when imaging with  $P_{\text{laser}} = 0.25$  and 0.5 mW was  $R = 34.6 \Omega$ , indicating a fully superconducting current path through the device, whereas for  $P_{\text{laser}} = 1.0$  mW the resistance was  $R = 50.2 \Omega$ , indicating a normal-state Nb film. All scale bars are 20  $\mu$ m. (g) Illustration of the temperature profile across the Nb channel at each of the laser conditions imaged. At  $P_{\text{laser}} = 0.25$  and 0.5 mW, the laser heats the channel reducing the critical current density as T approaches  $T_c$ . At  $P_{\text{laser}} = 1.0$  mW, Joule heating from the normal-state Nb dominates and gives a near-uniform temperature profile. (h) Line cuts of *x*-component of the current density,  $J_{xr}$ , across the same section of the Nb channel for  $P_{\text{laser}} = 0.25$  mW (purple), 0.5 mW (green), and 1.0 mW (orange). The location of the line cuts are indicated in (d–f). The edges of the Nb channel, indicated by vertical dashed lines, were identified from the ODMR contrast (see SI, Figure S11).

single-photon and single-electron detectors, which rely on quenching superconductivity at the site of detection.<sup>37,38</sup> Here we apply a biasing field,  $B_{app} = (47.5, 97.4, 19.1)$  G, to resolve the spin transitions of the different NV orientations and measure the net vector magnetic field,  $\mathbf{B} = (B_{xr} B_{yr} B_z)$ . This allows us to reconstruct the current density in the Nb device with good accuracy by inverting the Biot-Savart law<sup>39,40</sup> (see SI, Section XII). The Ørsted field was measured at three different laser powers,  $P_{\text{laser}} = 0.25$ , 0.5, and 1.0 mW, with a constant total current, I = 20 mA, for all measurements. We show only the field projected in the z-direction,  $B_{zr}$  as this was used to reconstruct the two-dimensional current density, J (see SI, section XII).

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At  $P_{\text{laser}} = 0.25$  and 0.5 mW,  $R = 34.6 \Omega$  for the duration of measurement (approximately 1 hour), indicating fully superconducting current pathways across the device (see Methods in SI). The measured  $B_z$  (Figure 4a,b) and the associated total current density, |J| (Figure 4d,e), show a nonuniform current density distribution that is more laterally confined at the lower laser power. At  $P_{\text{laser}} = 1.0 \text{ mW}$ ,  $R = 50.2 \Omega$ , indicating a fully normal-state current pathway, as expected from cascade Joule heating from the comparably large current. Consequently,  $B_z$ (Figure 4c) and IJI (Figure 4f) show a current distribution that is uniform across nearly the full width of the Nb channel. The current density tapers at the edge of the field of view due to a reconstruction error (see SI, Figure S14, where we show that |] reconstructed from  $B_{\nu}$  does not show this tapering effect). Note that imaging with  $P_{\text{laser}} = 0.5 \text{ mW}$  but using the heater to raise the temperature above  $T_c$  ( $T_{sensor} = 12$  K) gave results identical to the  $P_{\text{laser}} = 1.0 \text{ mW}$  case, for both the |J| map and the ODMR contrast.

The nonuniform current density through the superconducting-state Nb channel is a direct consequence of the temperature profile imprinted by the laser (Figure 4g). As the local temperature increases, the superconducting gap, and hence the critical current density,  $J_c$ , is reduced. The measured current density is therefore larger where the local temperature is lower. Increasing the total laser power reduces  $J_c$  across the channel, and the current density distribution broadens to maintain the same total current. Line cuts of the current density in the *x*-direction highlight this effect (Figure 4h). We note that the imaged |J| under fixed laser conditions retains a consistent shape across the Nb channel as the field of view is translated, indicating that the nonuniformity observed arises from the excitation laser, rather than local variation in the film (see SI, Figure S15).

In this work, we demonstrated a cryogenic wide-field NV microscope featuring a submicrometer spatial resolution and a field of view of 100  $\mu$ m and applied it to the imaging of vortices and transport currents in superconducting Nb devices. The demonstrated field of view is five times larger than in the previous demonstration of wide-field NV imaging at cryogenic temperatures, which reported a field of view of 20  $\mu$ m.<sup>20</sup> This new capability is ideal for spatially resolved investigations of mesoscopic phenomena in a variety of materials and devices and also enables imaging of several samples in parallel. For instance, atomically thin samples of van der Waals materials prepared by mechanical exfoliation typically come in the form of multiple micrometer-sized flakes with different properties (thickness, shape), and so wide-field imaging of such samples would allow simultaneous studies of many of them, greatly speeding up the characterization process. This could be

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particularly useful to investigate, for example, the magnetic properties of ferromagnetic van der Waals materials and heterostructures.

Our work also highlighted a limitation of NV microscopy for low-temperature measurements where the laser illumination required to optically interrogate the NV centers can lead to significant heating of the sample under study. Using the Nb superconducting film ( $T_c \approx 9$  K) as a local temperature probe, we found that even modest illumination powers (2 mW, corresponding to a peak intensity of  $40 \text{ W/cm}^2$ ) can locally quench the superconductivity of the film, implying that the sample temperature exceeds 9 K even when the temperature measured with a nearby sensor remains below 5 K, close to the base temperature of the cryostat. This work thus demonstrates the need for caution in NV sensing experiments at low temperature, setting a limit on the laser power that can be used for minimally invasive imaging. In our experiments, a total power of 0.5 mW (peak intensity of 10 W/cm<sup>2</sup>) was sufficiently low to keep the Nb devices fully superconducting, allowing an array of frozen superconducting vortices to be imaged. Although the acceptable illumination conditions will depend on the details of the experimental setup and sample under study, it is likely that the most sensitive samples will require strategies to mitigate laser-induced heating. These include the introduction of a thin high-reflectance metallic film between the diamond and sample of interest, the use of better thermal conductors between the sample and the cooling elements of the cryostat, or the implementation of an optimized illumination geometry to reduce the required laser power. These precautions may be necessary even in single NV experiments which can have similar laser power densities at the point of imaging despite using less total power. Such steps will unlock the potential of NV microscopy for a broader range of low-temperature condensed matter phenomena.

## ASSOCIATED CONTENT

## Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.9b05071.

Details on sample fabrication, experimental setup, analysis of the ODMR measurements, transport current reconstruction, theoretical modeling of vortex heating, and additional data and discussion of microwave heating, magnetic field dependence, cooling rate dependence, and ODMR contrast reduction (PDF)

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#### Notes

The authors declare no competing financial interest.

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