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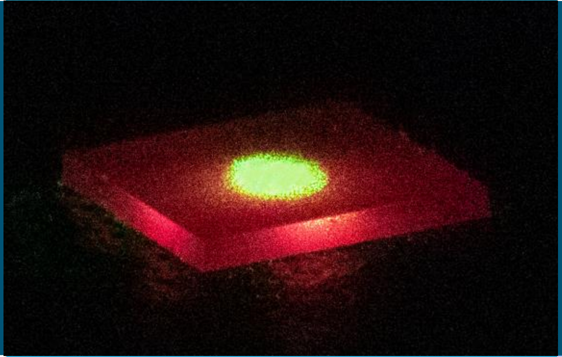
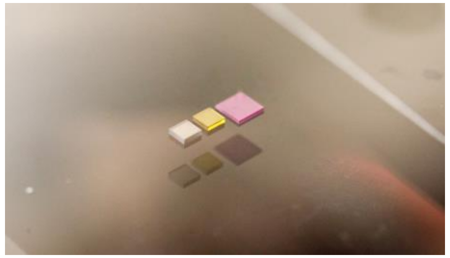
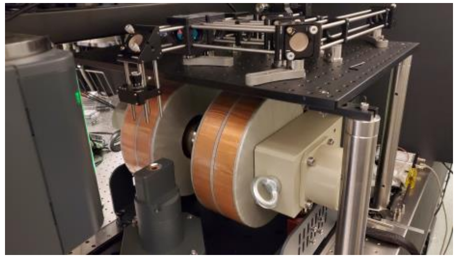
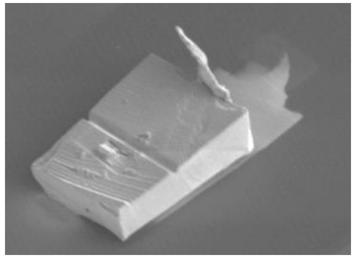
Sandia National Laboratories

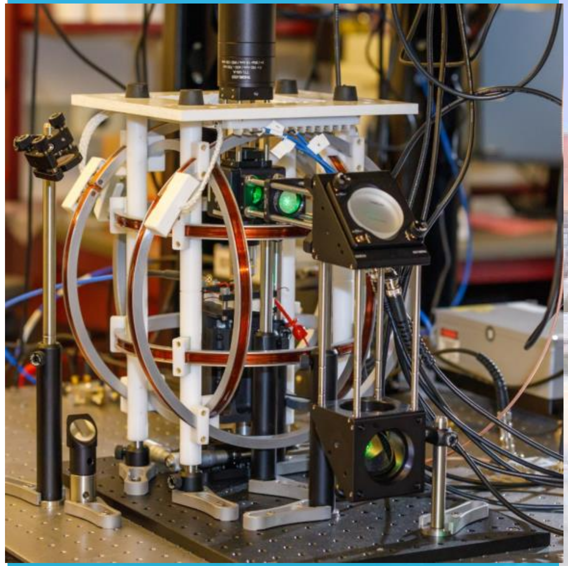
Current Paths in an Atomic Precision Advanced Manufactured Device Imaged by Nitrogen Vacancy Diamond Magnetic Microscopy











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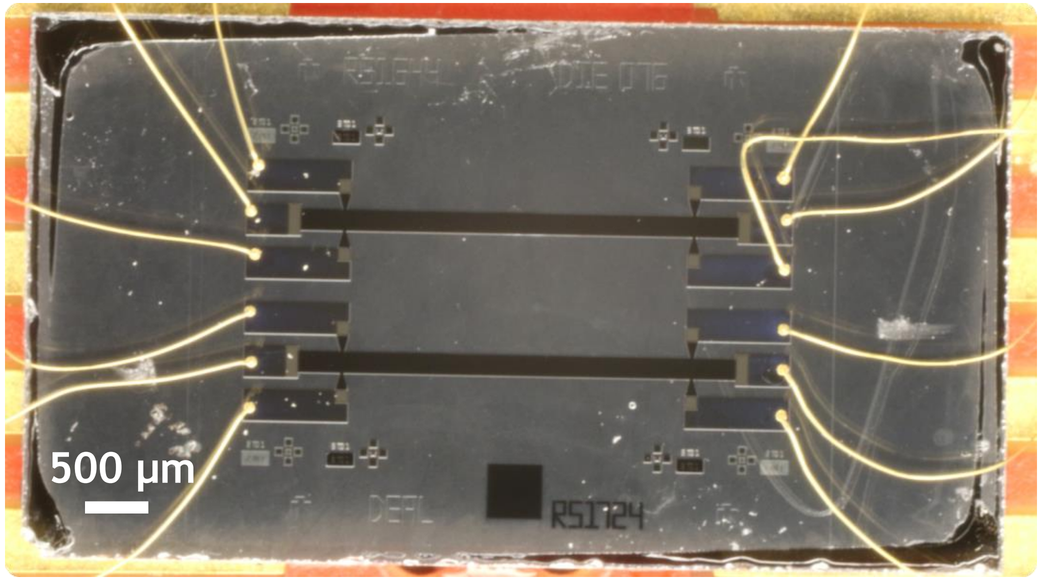
Outline

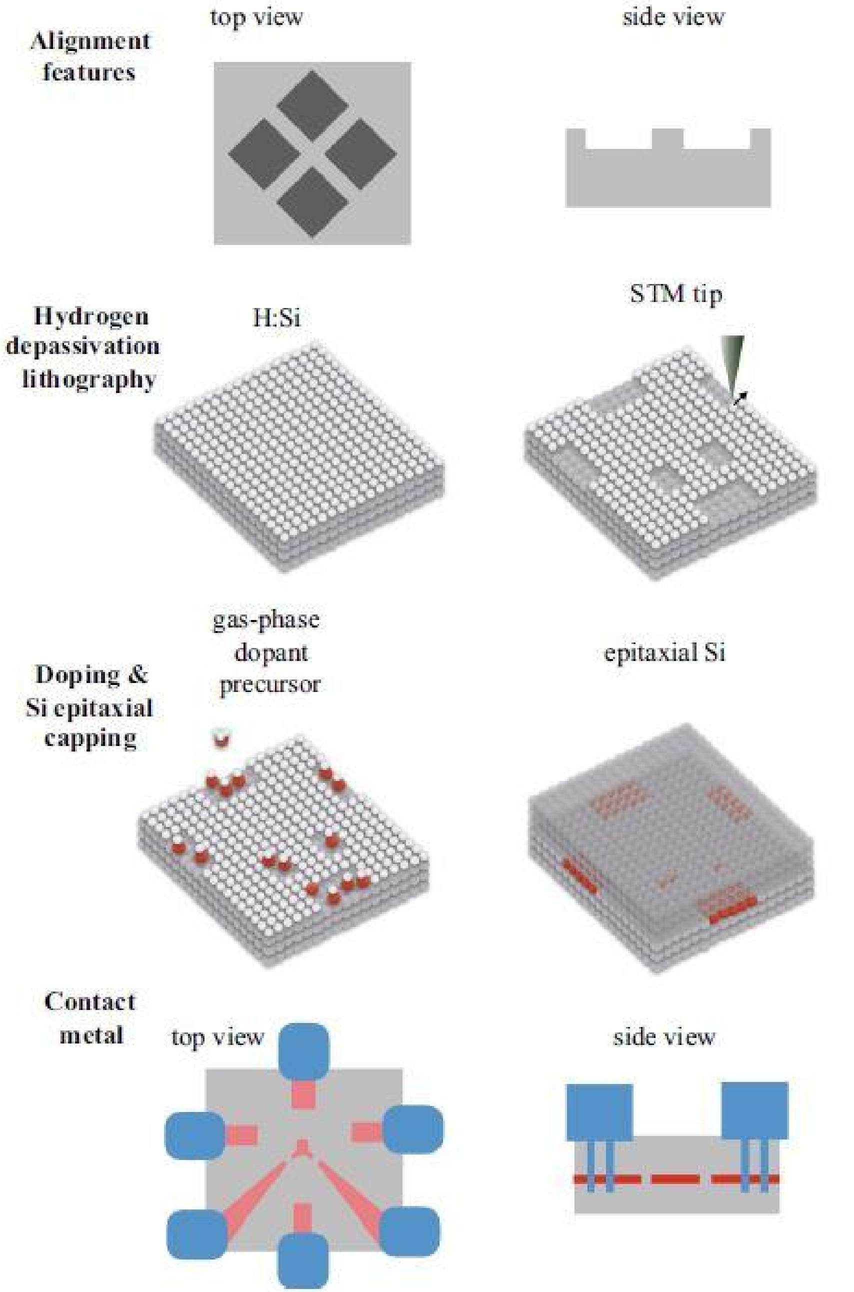
- Introduction on atomic-precision-advanced-manufactured (APAM) devices
- Nitrogen-Vacancy (NV) centers in diamond.
- Wide-field magnetometry based on NV centers.
- Experimental results:
  - APAM devices magnetic field map and current reconstruction
  - Working device vs broken device
- Conclusions

APAM device

- Atomic-precision-advanced-manufactured (APAM) Si:P D-doped materials are a channel to new microelectronics technologies based on quantum-confined 2D electron-transport in Si.
- APAM devices are fabricated by selective doping on a lithographically defined pattern in a silicon template.
- In this case, the APAM device is patterned into an electric device shaped like mm-sized ribbons



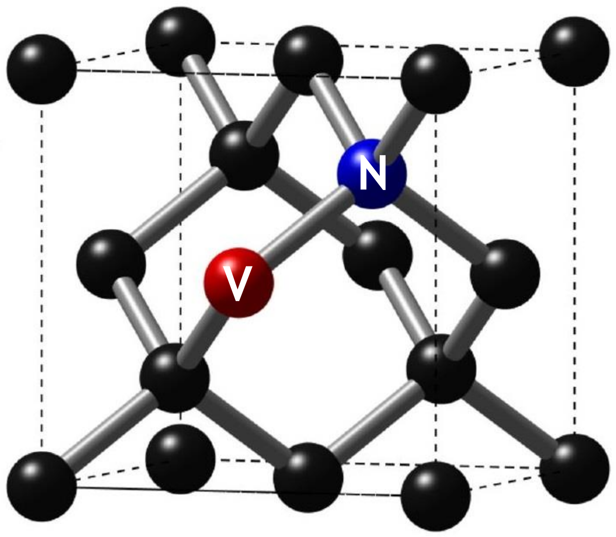
APAM device, provided by S. Mistra et al. at SNL



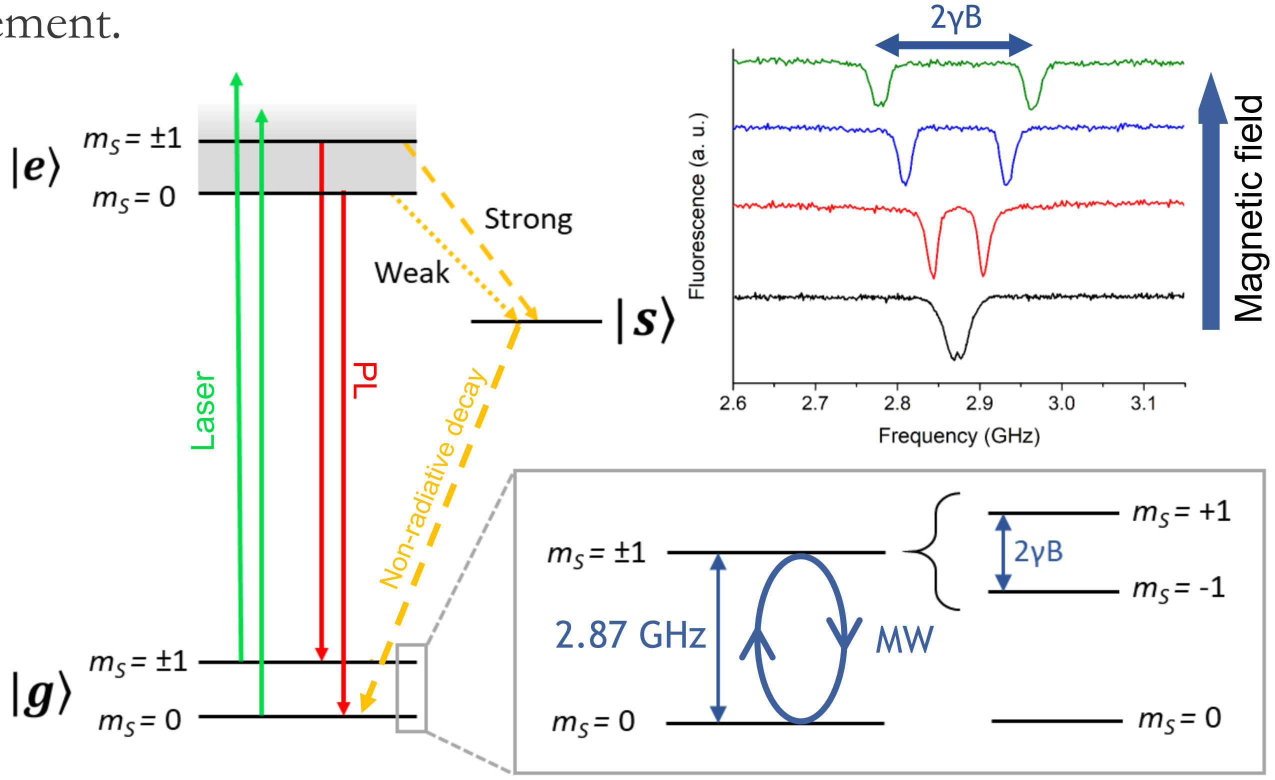
APAM fabrication process. From Bussmann et al. MRS Bulletin 46, 607 (2021)

Nitrogen Vacancy (NV) centers

- Point defect in diamond consisting of a substitutional nitrogen and carbon vacancy.
- The defect's electronic spin population (S=1) can be manipulated by a microwave field and readout optically, allowing for Optically Detected Magnetic Resonance(ODMR)
- Spin sublevel degeneracy can be removed by external perturbations (e.g. magnetic fields), allowing their measurement.



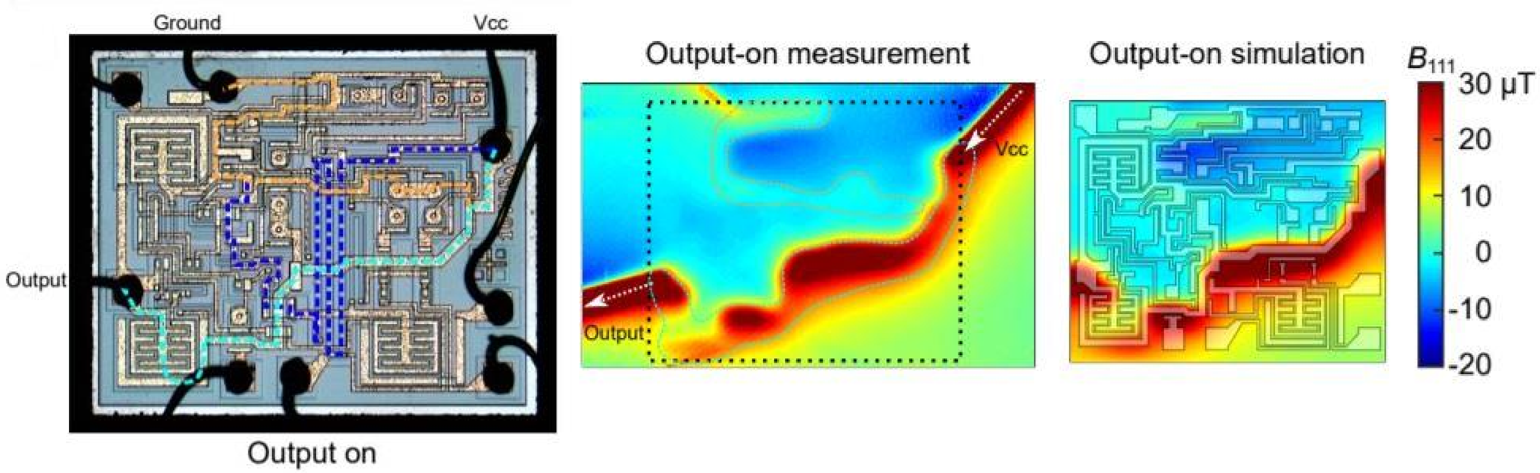
NV crystal structure



NV spin states and ODMR spectrum

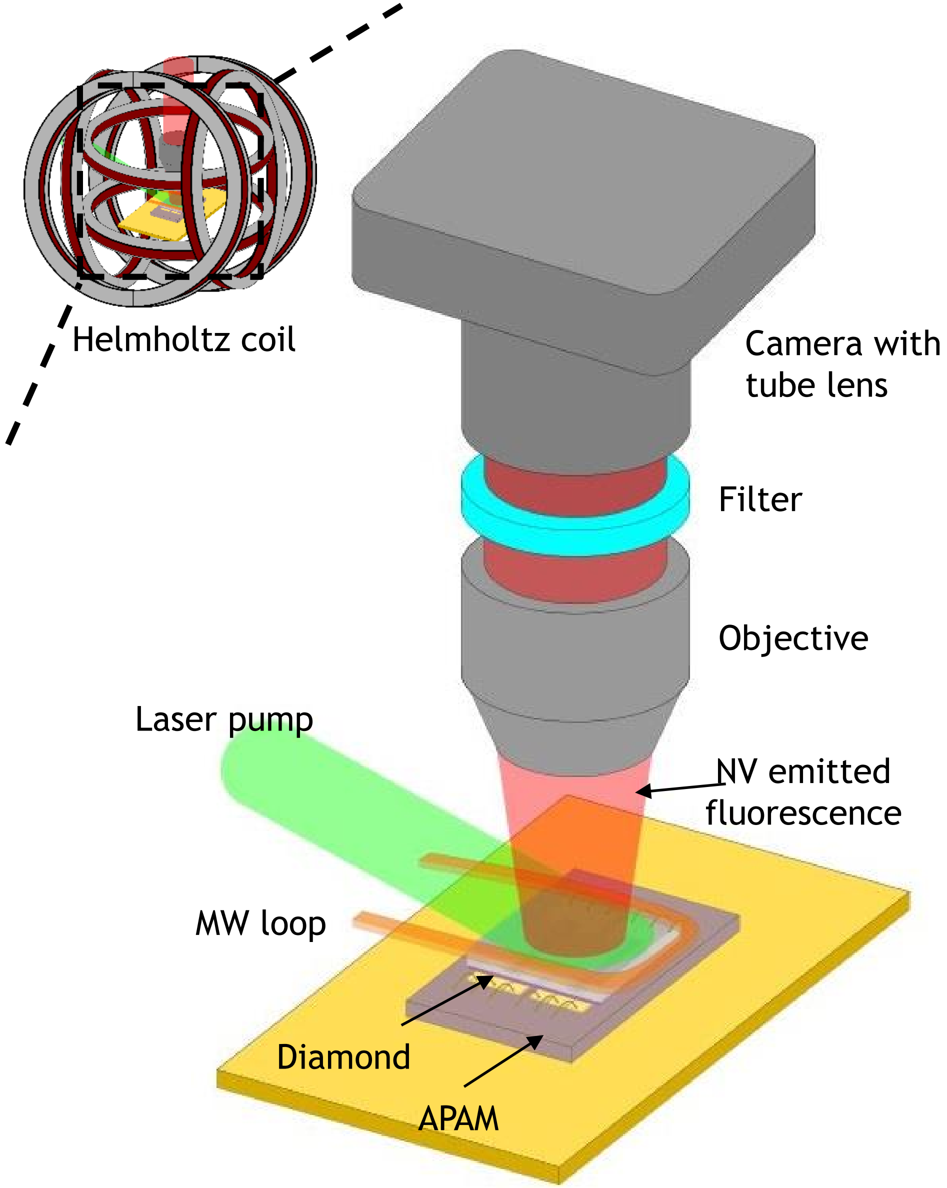
NV wide-field microscope

- Wide-field NV magnetometry is non-invasive technique that provides large field of views with high lateral resolution.



NV magnetic imaging of a 555 IC.
From Kehayias et al. Phys. Rev. Appl. 17, 014021 (2022)

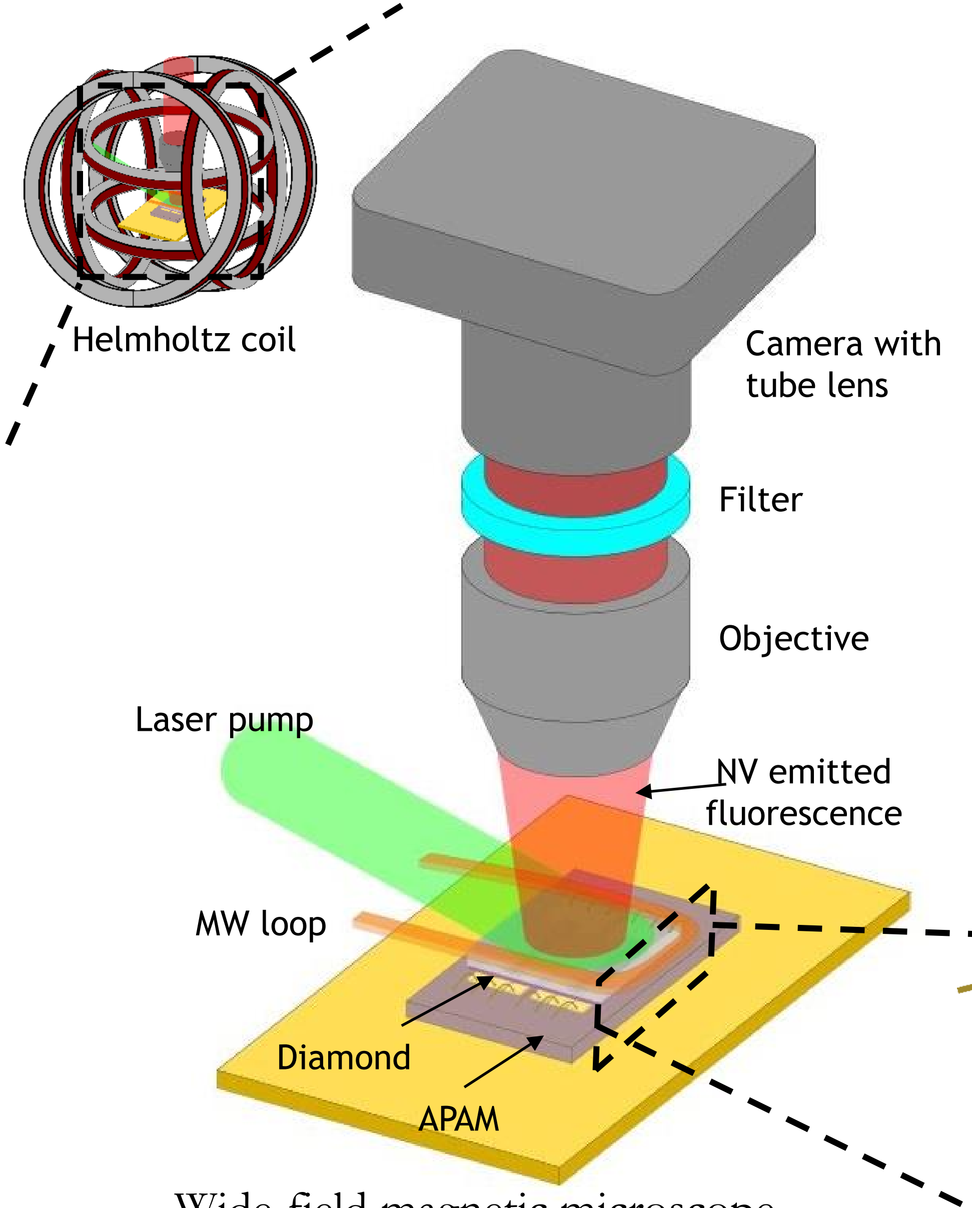
NV wide-field microscope



Wide-field magnetic microscope

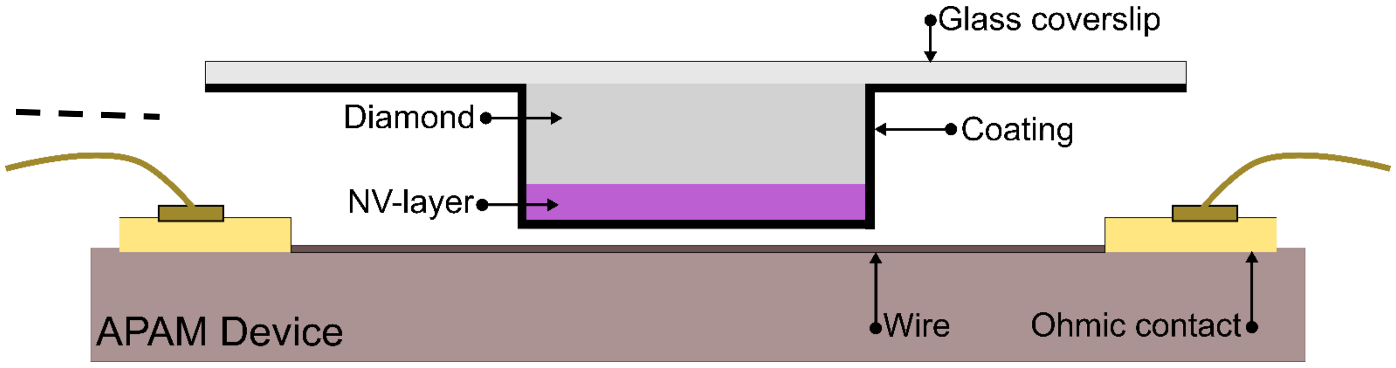
- Wide-field NV magnetometry is non-invasive technique that provides large field of views with high lateral resolution.
- Currents flowing in atomic precision advanced manufactured (APAM) wires are imaged with NVs in bulk diamond in a wide field microscope.

NV wide-field microscope



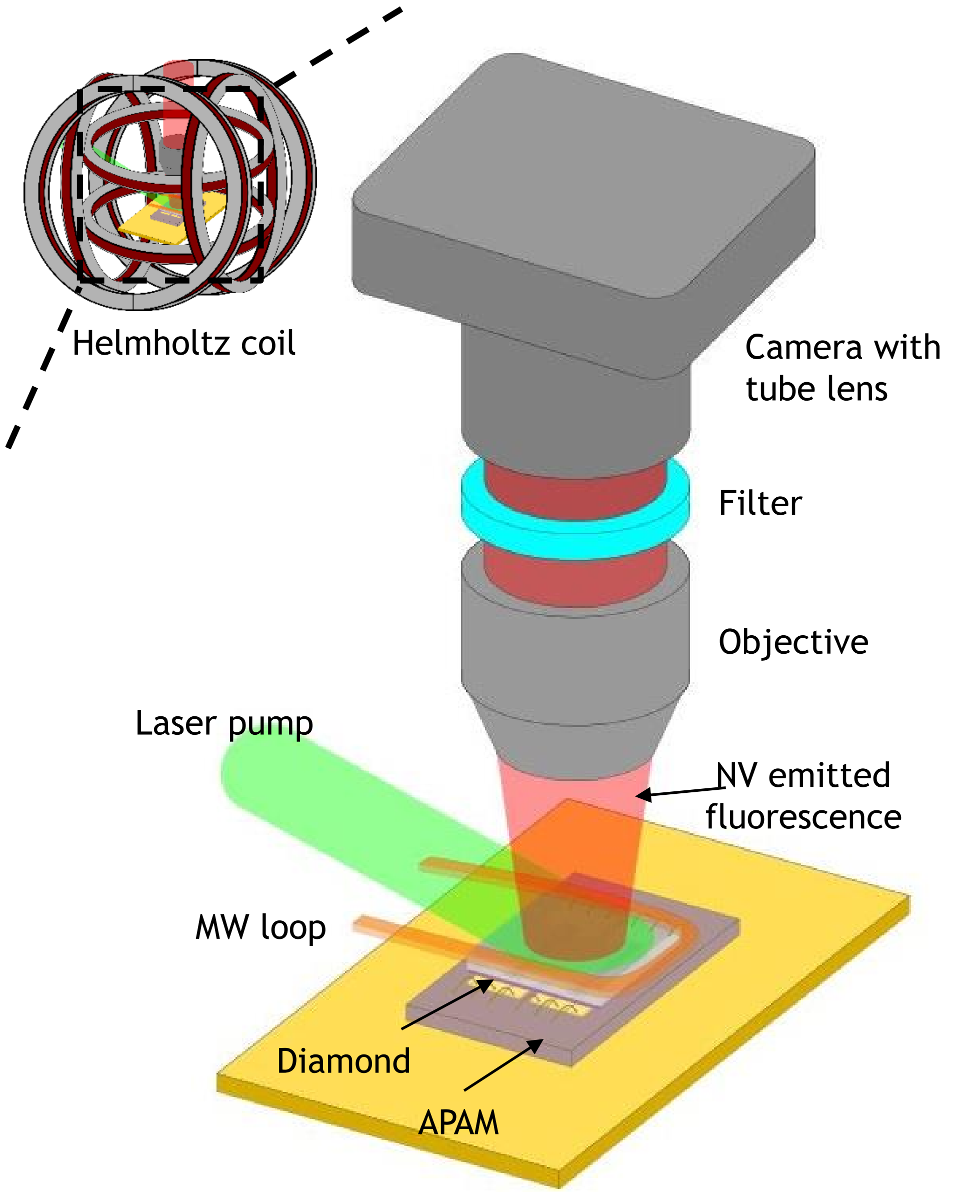
Wide-field magnetic microscope

- Wide-field NV magnetometry is non-invasive technique that provides large field of views with high lateral resolution.
- Currents flowing in atomic precision advanced manufactured (APAM) wires are imaged with NVs in bulk diamond in a wide field microscope.
- Diamond sensor (4μm-thick NV layer) coated with reflective coating (3nm Ti, 150nm Ag, 150nm Al_2O_3).



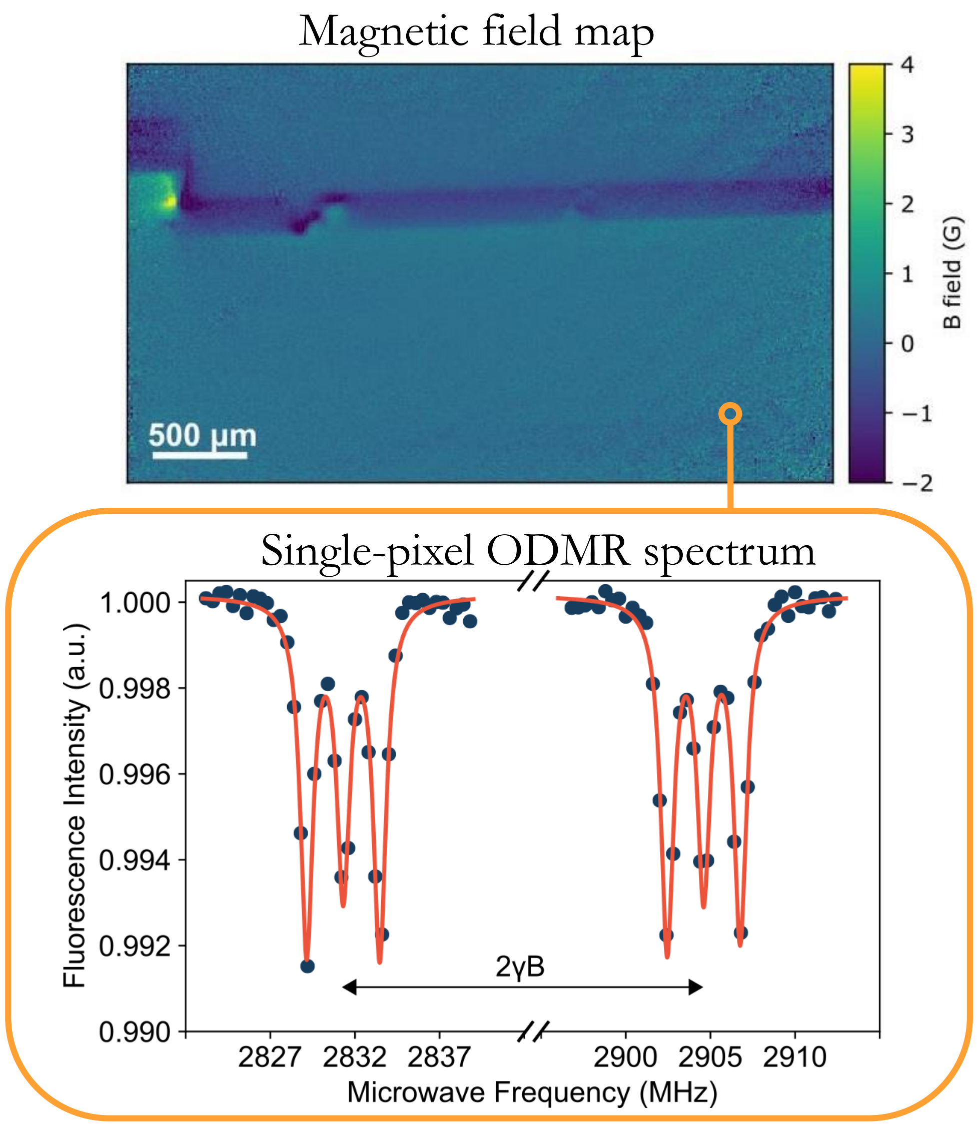
Diamond sensor-device integration

NV wide-field microscope

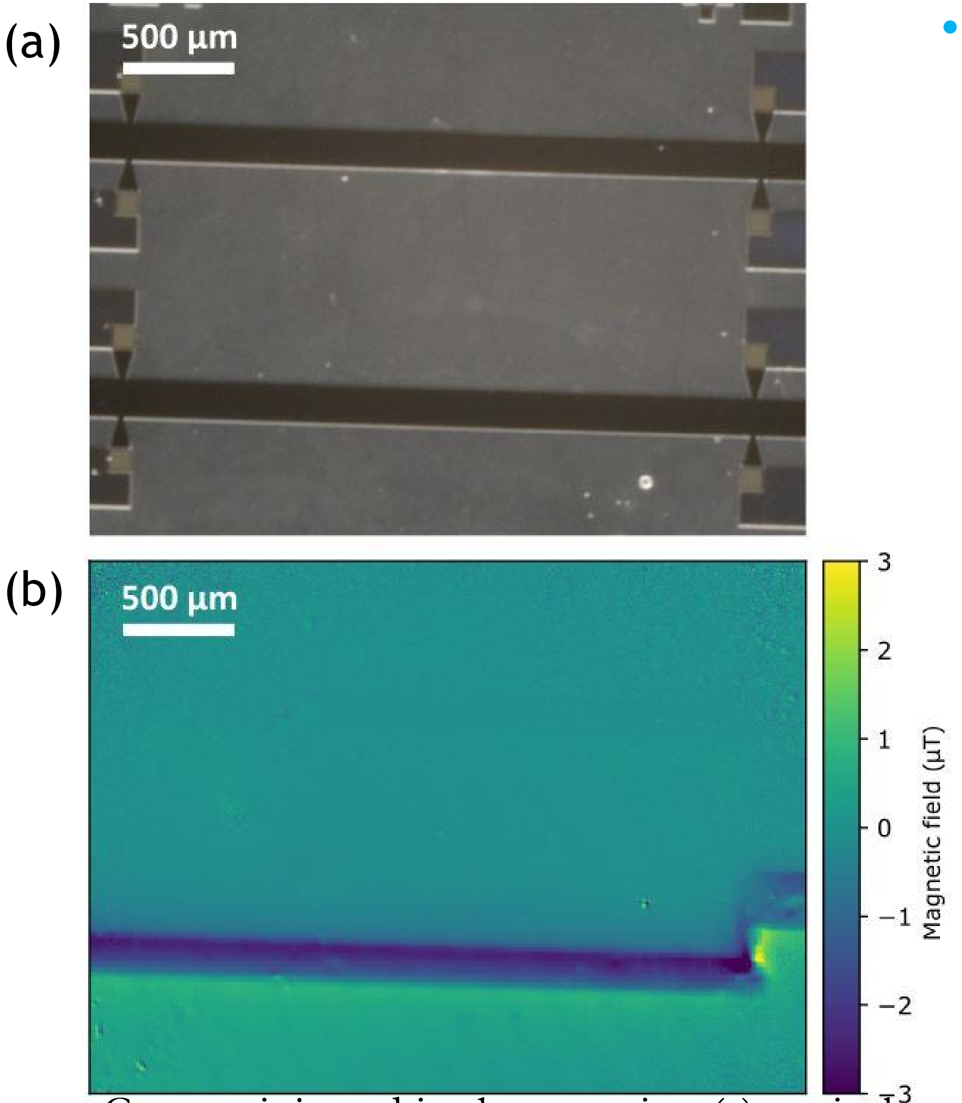


Wide-field magnetic microscope

- Wide-field ODMR allows to obtain local magnetic field measurement from each camera pixel.



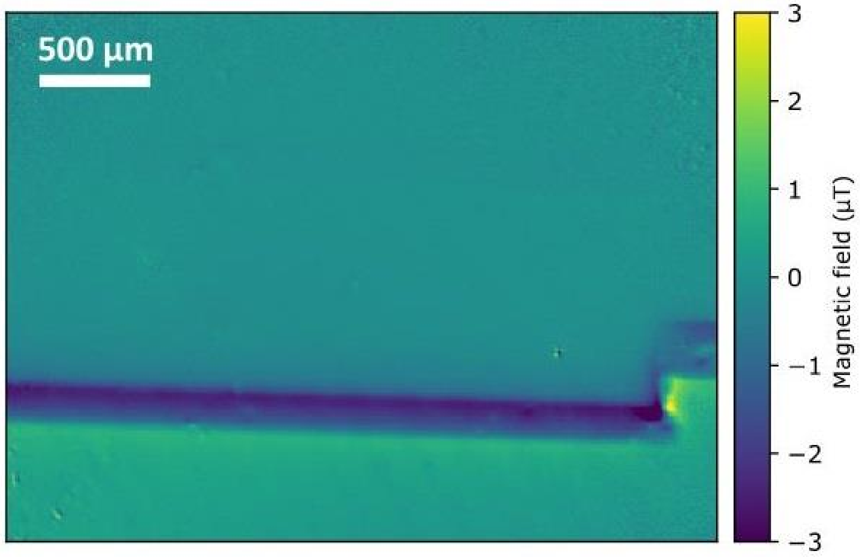
Experimental result: Magnetic field maps



Current injected in the top wire: (a) optical image, (b) magnetic field map

- Magnetic field *B* generated by current *J* flowing into the patterned wires is mapped by the NV ensemble.

Experimental result: Magnetic field maps



- Magnetic field *B* generated by current *J* flowing into the patterned wires is mapped by the NV ensemble.
- From the magnetic field map, the surface current density can be reconstructed [1]:

Biot-Savart law: $$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int d^3\mathbf{r}'\frac{\mathbf{J}(\mathbf{r}')\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}$$

Continuity equation: $$\nabla\cdot\mathbf{J} = 0$$

By inverting Biot-Savart law with a Fourier analysis approach:

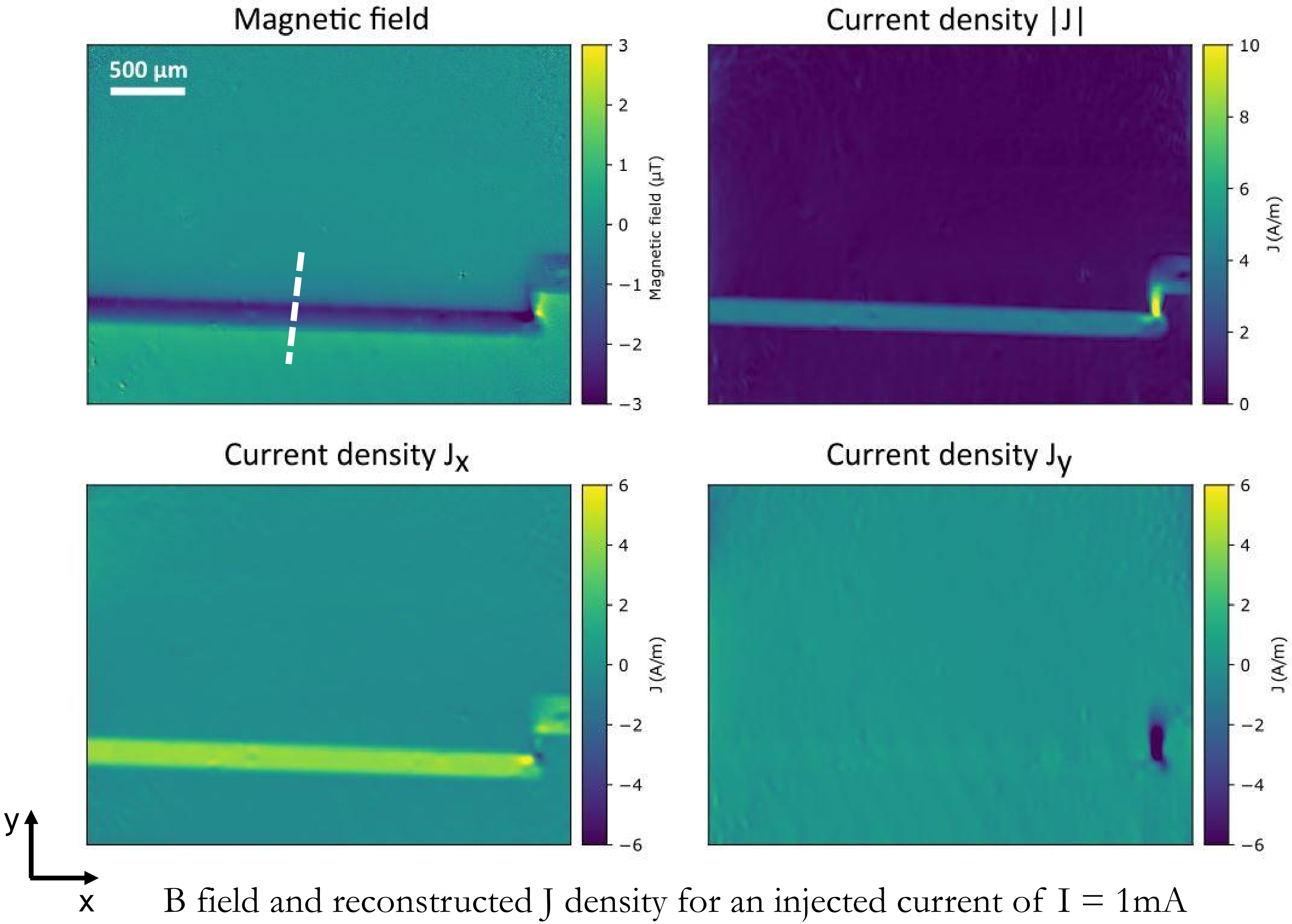
$$J_x = \frac{w}{g[e_y - e_x\frac{k_x}{k_y} + ie_z\frac{k}{k_y}]}B_{||}$$

$$J_x = \frac{w}{g[e_x - e_y\frac{k_y}{k_x} + ie_z\frac{k}{k_x}]}B_{||}$$

- $g = \frac{\mu_0}{2}e^{-kz}$ with z being the **stand-off distance**
- (e_x, e_y, e_z) is the vector pointing along NV axis,
- k_x and k_y are the the k-vectors for x and y, $k = \sqrt{k_x^2 + k_y^2}$
- *w* is the Hanning filter function

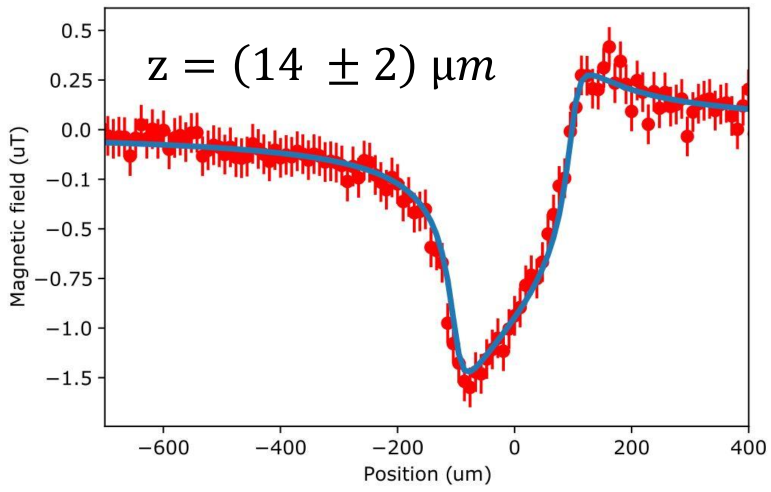
[1] Chang et al. *Nano Lett.* 2017, 17, 4, 2367–2373

Experimental result: Current reconstruction



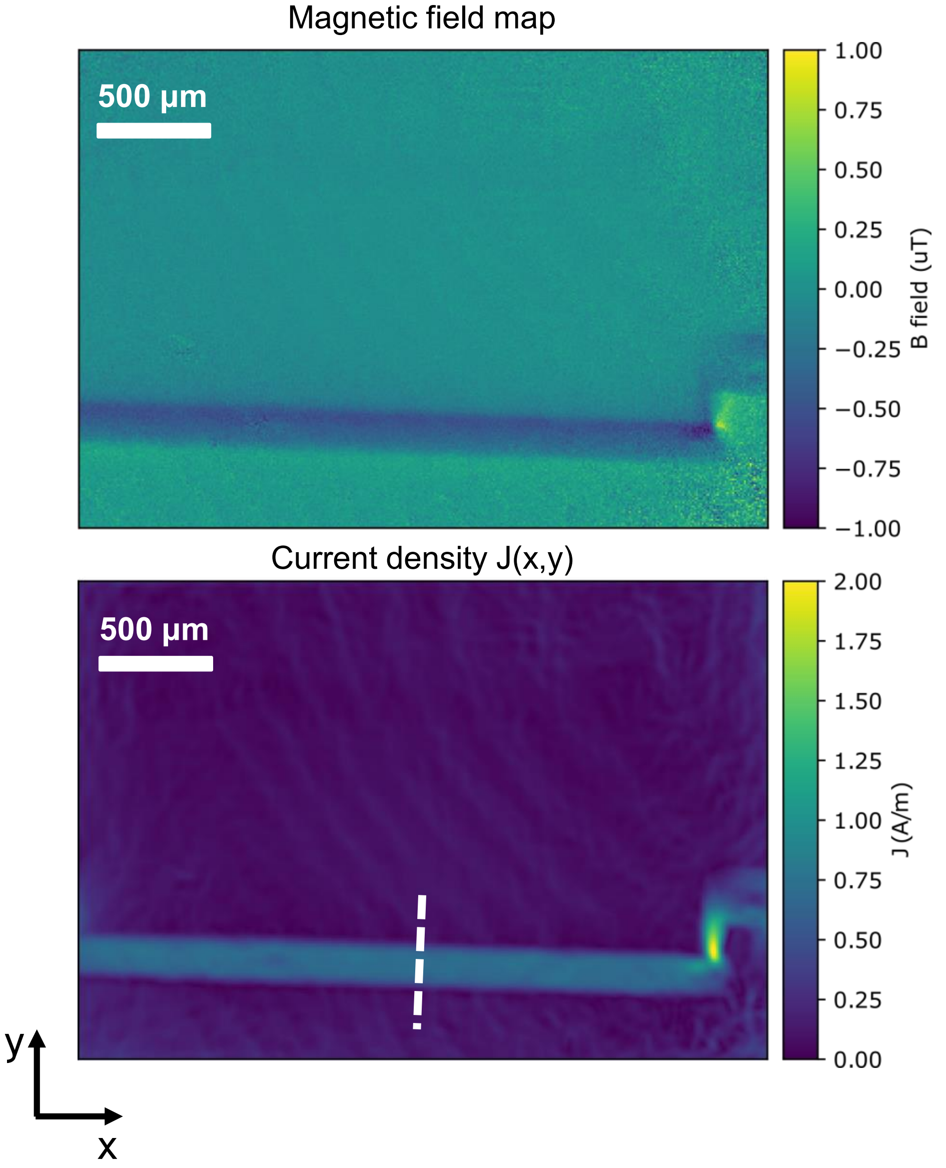
B field and reconstructed J density for an injected current of I = 1mA

- Stand-off distance h is required to reconstruct the current density:

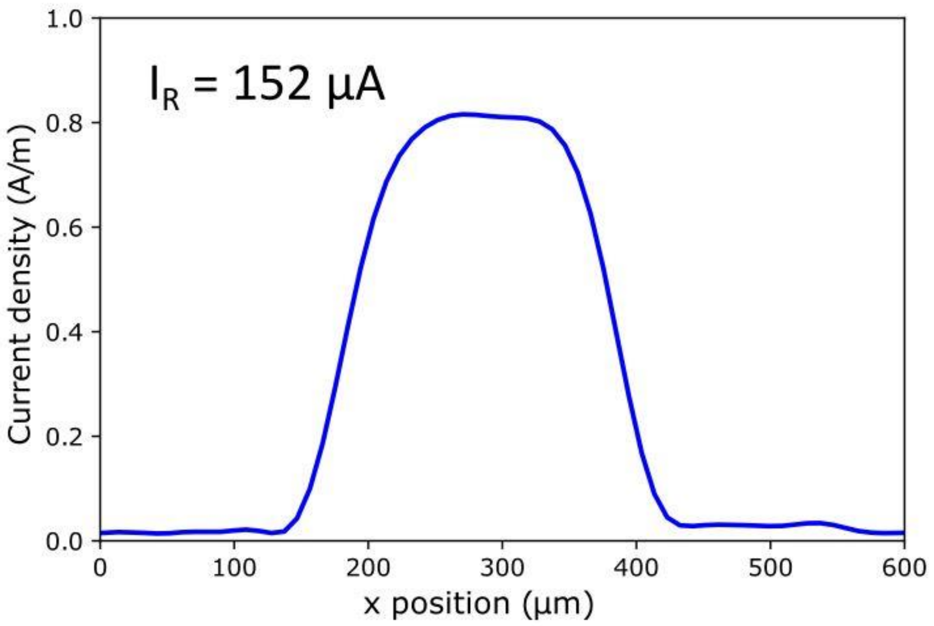


Magnetic field measured along dashed line for stand-off distance estimation.

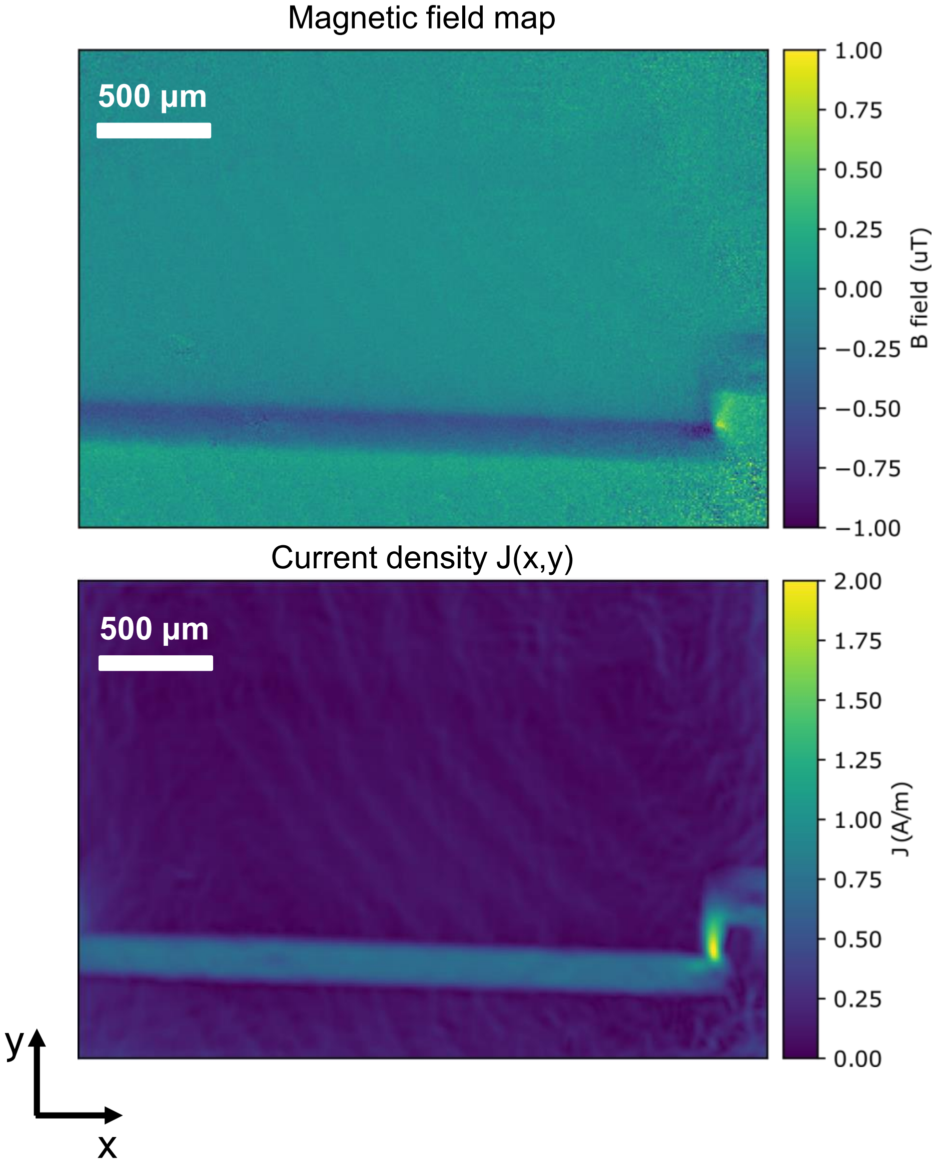
Experimental result: working device



- Reconstructed current $I_R = 152\ \mu\ A$ matches the injected current $I = 150\mu A$

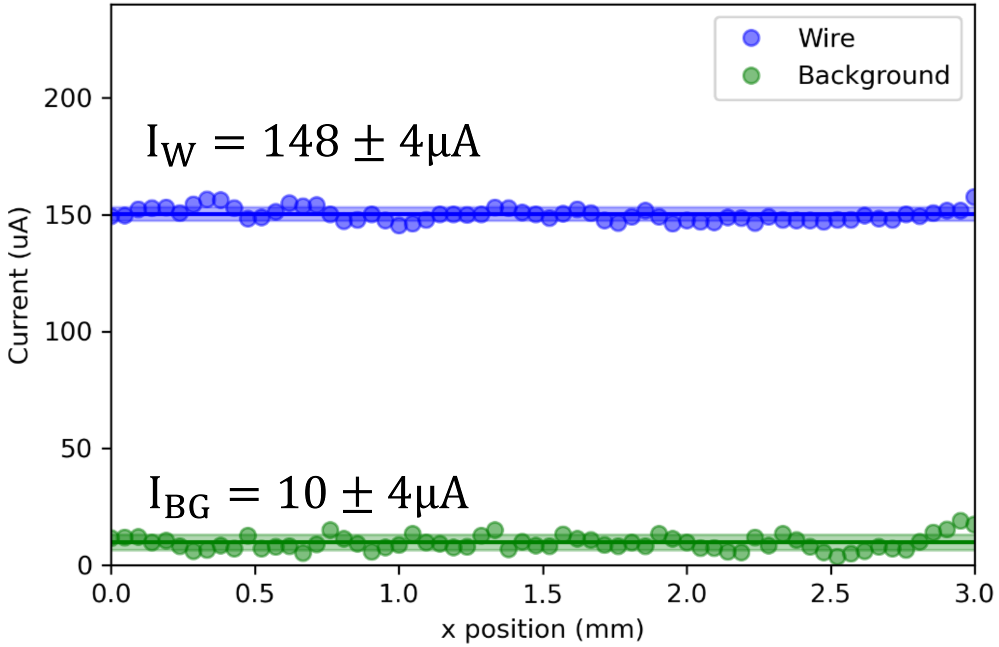


Experimental result: working device



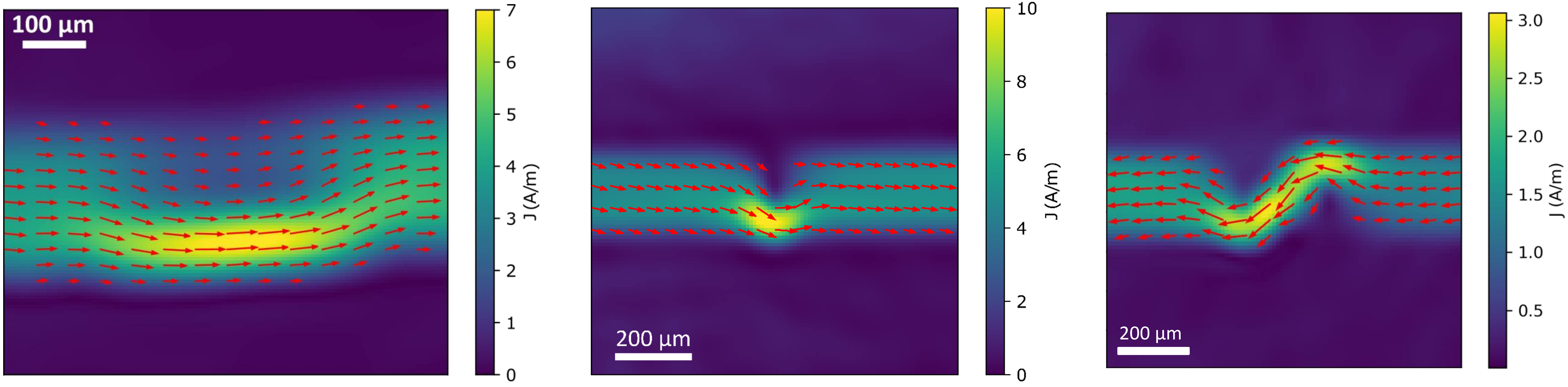
- Uniformity of the current along the wire is studied for an injected current of $I = 150\ \mu A$
- Background current is also measured, giving us an estimate of the smallest current detectable.

Current integrated along the wire I_W and in the background I_{BG}



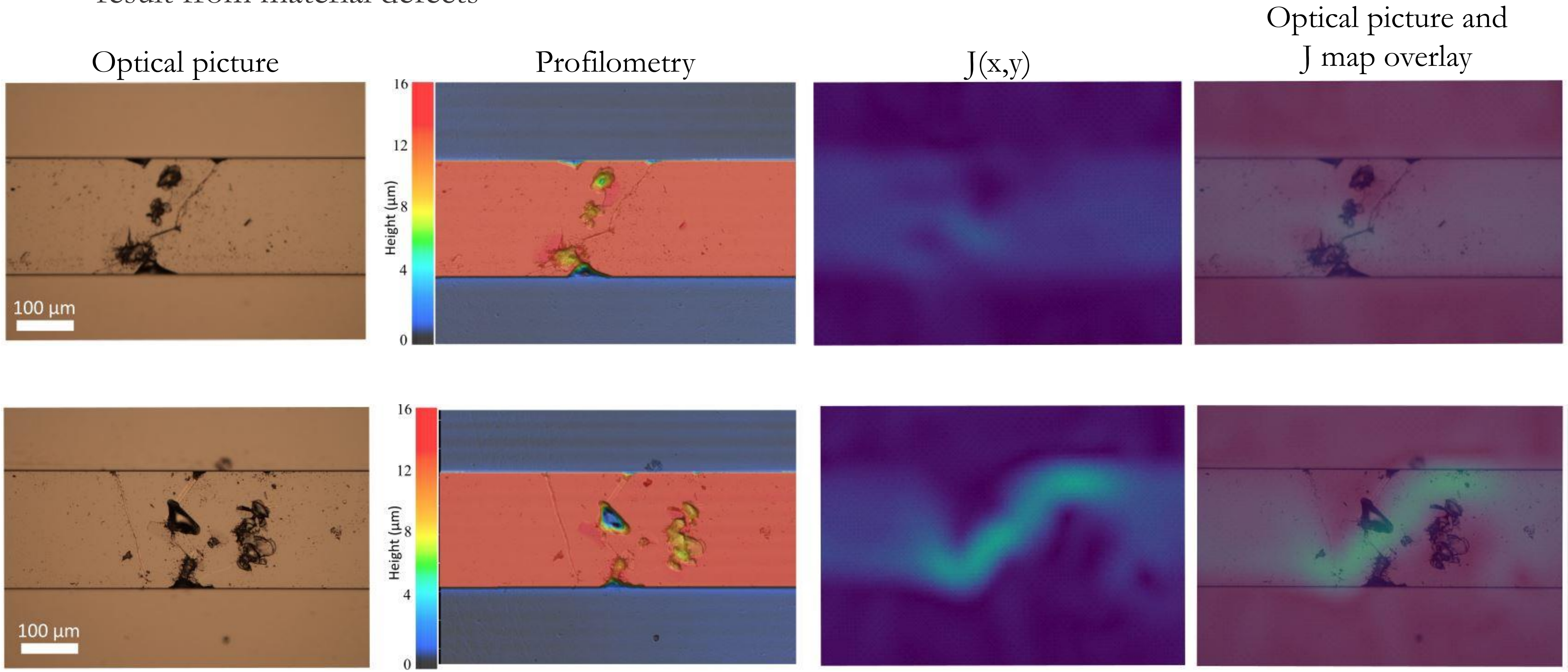
Experimental result: broken device

- From the surface current density $\{J_x, J_y\}$ the current flowing direction is also obtained.
- Sections of the wire where current is impeded can be observed.



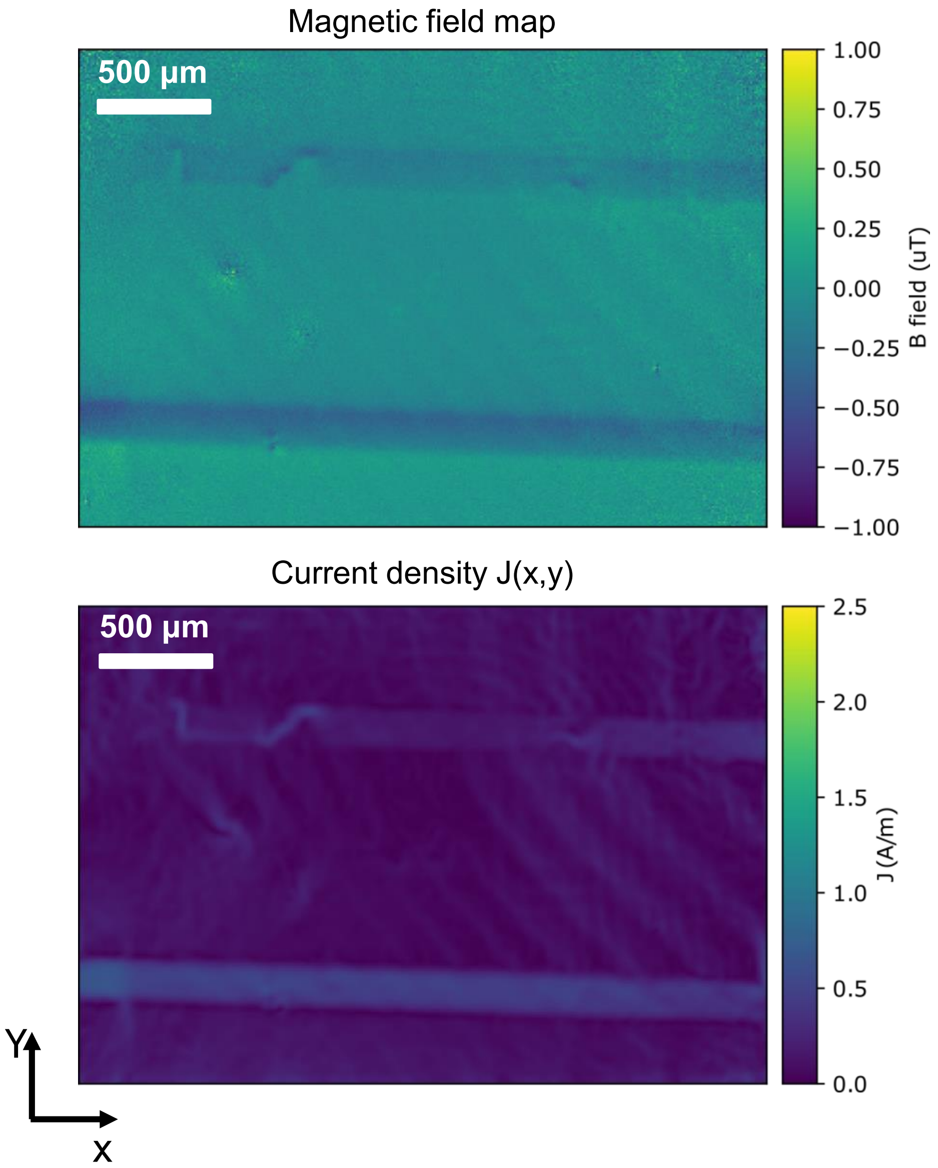
Experimental result: device features

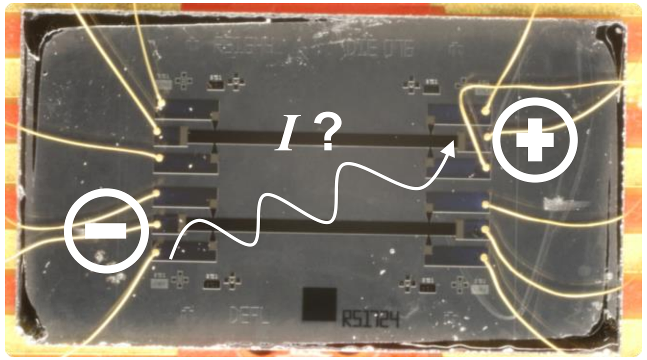
- Comparison between optical pictures and current maps allows to conclude that choke points result from material defects



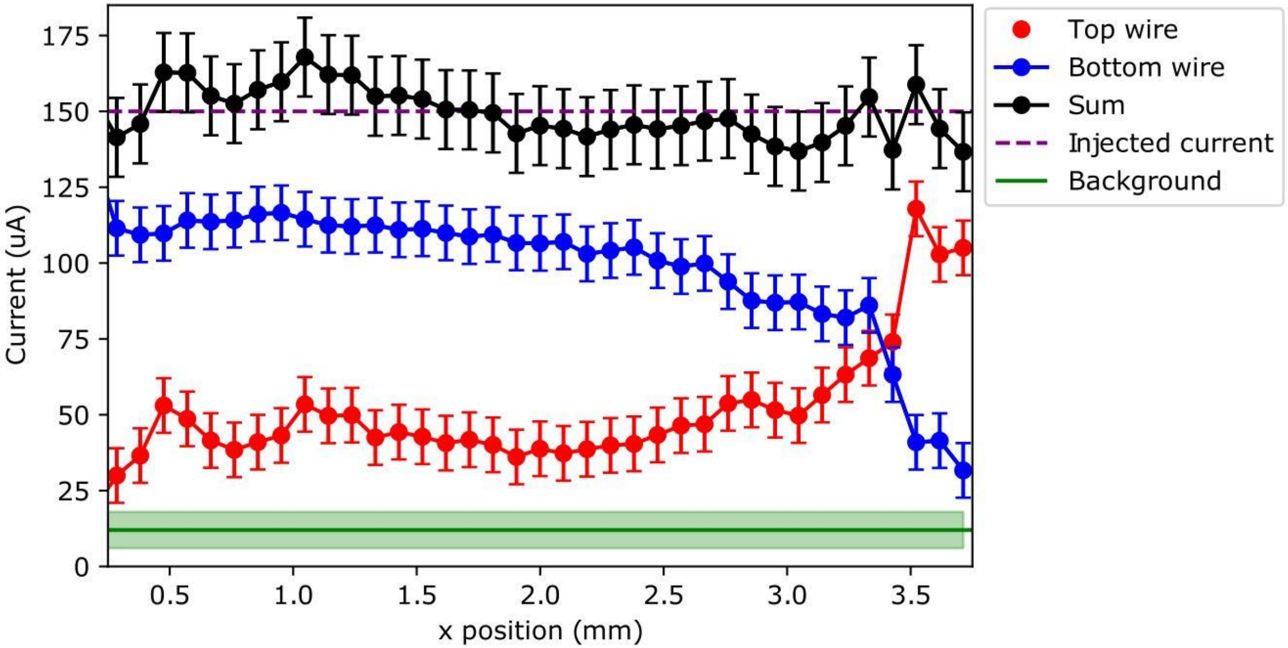
Scale bar is the same for all the pictures.

Experimental result: leakage path



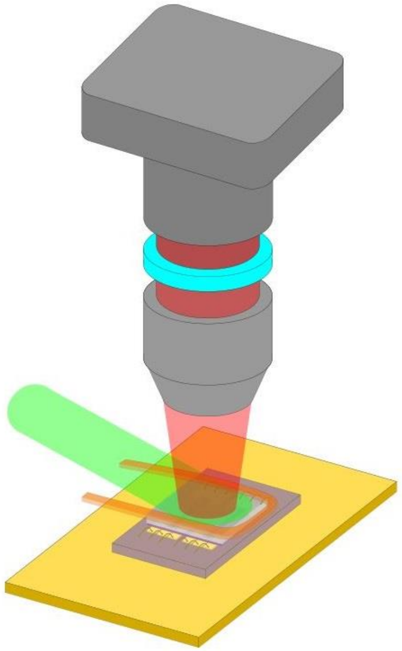


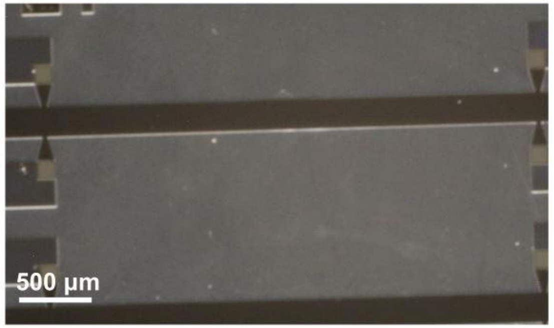
- NV magnetometry used to measure current leaks between the two wires
- Direct observation of the leak path is not obtained.



Conclusions

- Diamond NV-center wide field imaging is a promising magnetic field diagnostic tool, allowing millimeter-scale field of view and micron-scale spatial resolution at ambient condition.
- From the APAM B-field map we reconstructed the *J* density vector field, which allowed us to detect device failures.
- Our results bode well for leveraging extreme lithographic precision of APAM devices in technologies at T≥300K.





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