Scanning SQUID-on-tip nanothermometry of quantum systems

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[Logos for European Research Council, Binational Science Foundation, etc.]
**SQUID on tip**

SC lead → SC lead

SQUID loop → Ø 30 weak links

Al, Nb, Pb, In, Sn

Loop diameter = 46 nm

Flux noise: $\sqrt{S_\Phi} = 50 \text{n}\Phi_0/\text{Hz}^{1/2}$

Spin noise: $\sqrt{S_n} = 0.38 \text{ } \mu_B/\text{Hz}^{1/2}$

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
Magnetic phenomena on the nanoscale

Vortex matter

Vortex dynamics

Nanomagnetism

Magnetic TI

Oxide interfaces

Multijunction SOT
Thermal imaging

dissipation
SOT thermal and magnetic sensitivity

Magnetic sensitivity

\[ I_c \rightarrow H \]

\[ \mu_0 H \]

Pb SOT

\( T = 4.2 \text{ K} \)

Thermal sensitivity

\[ T \]

\[ 4.2 \text{ K} \]

\[ 7.2 \text{ K} \]
Thermal imaging techniques

- Plasmon TEM
- SNOM
- TC SThM
- Res. SThM
- Nanodiamond

Sensitivity [K/Hz$^{1/2}$]

Size [nm]

Current noise

$S_T^{1/2} = 870 \text{ nK/Hz}^{1/2}$

Thermal response

$-9.5 \mu A/K$

Thermal noise:

$S_T^{1/2} = 870 \text{ nK/Hz}^{1/2}$
Thermal imaging techniques

Thermal noise:
\[ S_T^{1/2} = 870 \text{ nK/Hz}^{1/2} \]
Figure of merit:
Landauer's limit of energy dissipation for irreversible qubit readout

\[ E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J} \]

Qubit at 1 GHz:

\[ P = 40 \text{ fW} \]
Multifunctional imaging

$B_z \, [\mu T]$  

$I_{ac} = 10 \, \mu A$  
$f = 6.5 \, kHz$

$B_z^{dc} \, [mT]$

$H_{||}$

$H_z$

dc magnetic field

$ac$ magnetic field

$ac$ magnetic field at $f$

$B_z^{ac} \, [\mu T]$

$T_{ac} \, [mK]$

$ac$ temperature at $2f$

D. Halbertal et al., Nature 539, 407 (2016)
Dissipation in carbon nanotubes

Woodside and McEuen 2002

D. Halbertal et al., Nature 539, 407 (2016)
Dissipation in hBN encapsulated graphene

D. Halbertal et al., Nature 539, 407 (2016)
Vacancies and adatoms form localized states near Dirac point in graphene.

Pereira et al., PRL 96 (2006)
Bistritzer & MacDonald, PRL 102 (2009)
Song, Reizer & Levitov, PRL 109 (2012)
González-Herrero et al., Science 352 (2016)
Mao et al., Nat. Phys. 12 (2016)

I_{dc} = 3 \mu \text{A}

V_{tg} = 2.0 \text{ [V]}

V_{bg} = 2 \text{ [V]}

I_{dc} = 3 \mu \text{A}

\text{Vacancies and adatoms form localized states near Dirac point in graphene.}

Dissipation from a single atomic defect in graphene

Pereira et al., PRL 96 (2006)
Bistritzer & MacDonald, PRL 102 (2009)
Song, Reizer & Levitov, PRL 109 (2012)
González-Herrero et al., Science 352 (2016)
Mao et al., Nat. Phys. 12 (2016)

I_{dc} = 3 \mu \text{A}

T_{ac} = 40 \mu \text{K}

300 \text{ nm}

Atomic source of phonons

hBN/Gr/hBN

SiO_{2}/Si
Resonant inelastic scattering by a single localized state.
Spectroscopy of bulk defects

$V_{bg} = 2.00$ [V]

$V_{tg} = 4.20$ [V]

Cooling power spectrum of the localized state

$\delta E = 13$ meV
Spectroscopy of edge defects

Energy of the localized states vs. position

Cooling power spectrum of the localized state

\[ \Delta E = 13 \text{ meV} \]
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Summary

Nanoscale thermal imaging of quantum systems with sub 1 μK sensitivity

Dissipation in quantum dots in CNT

Dissipation dominated by edge detects in graphene

Spectroscopy of edge states in graphene

Inelastic electron scattering by a resonant localized state

Detection of phonon emission from a single atomic defect
Available thermal microscopy techniques

- **Plasmon energy expansion**

- **Thermo-couple SThM**
  - Kim et al., ACS Nano (2012)

- **Resistive SThM**

- **IR thermal imaging**

- **Raman spectroscopy**

- **Fluorescence in nanodiamonds**
Edge defects spectroscopy

$V_{tg} = 10\ [\text{V}]$

$V_{bg} = 9\ [\text{V}]$

$V_{tg} = 9\ [\text{V}]$

$V_{bg} = -10.0\ [\text{V}]$
Edge defects statistical analysis

\[ T_{ac} [\mu \text{K}] \]

\[ V_{bg} [\text{V}] \]

\[ V_{tg} = -10 \text{ V} \]

\[ \Delta x [\text{nm}] \]

\[ \rho \sim \exp(-\Delta x_{nn} \rho) \]

\[ V_{LS} [\text{V}] \]

\[ x_i [\mu \text{m}] \]

\[ \Delta V [\text{V}] \]

\[ \rho = 135 \text{ defects/3.5 } \mu \text{m} \sim 40 \text{ defects/} \mu \text{m} \]
Dominance of atomic defect resonant inelastic scattering

Thermal imaging at Flat-Band conditions reveals undisturbed map

Dissipation dominated by ballistic phonon emission at structure edges
Thermal sensitivity

Figure of merit:
Landauer's limit of energy dissipation for irreversible qubit readout

\[ E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J} \]

Qubit at 1 GHz:

\[ P = 40 \text{ fW} \]
\[ \frac{dR_d}{dT} = -2.4 \text{ k}\Omega/\text{K} \]

\[ \frac{dl_{tSOT}}{dT} = -10 \mu\text{A/}K \]
$T_{ac}^s$ [mK]

$p$ [mbar]

$R_{ss} = 0.9 \times 10^{10}$ K/W
Thermal imaging
Static tSOT spectroscopy - experiment

\[ V_{bg} = V_{bg}^{LS} = 0.2 \text{ V} \]

\[ \delta E = 13 \text{ meV} \]

Wehling et al., PRB 80, 85428 (2009)
SQUID on tip

SC lead → SQUID loop → weak links

SC lead

Al, Nb, Pb, In, Sn

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
SQUID on tip

Quantum interference patterns

SQUID current \( (T = 4.2\, \text{K}) \)

\[
\begin{align*}
V [V] \quad &\quad 3 \quad &\quad 2 \quad &\quad 1 \quad &\quad 0 \quad &\quad -0.5 \\
B [T] \quad &\quad 0 \quad &\quad 0.5
\end{align*}
\]

Period = 103 mT \quad Loop diameter = 160 nm

Flux noise: \( \sqrt{S_\Phi} = 50\, \text{n}\Phi_0/\text{Hz}^{1/2} \)

Field noise: \( \sqrt{S_B} = 5.1\, \text{nT}\text{Hz}^{1/2} \)

Spin noise: \( \sqrt{S_n} = 1.4\, \mu_\text{B}\text{Hz}^{1/2} \)

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
Pb SQUID on tip

Quantum interference patterns

SQUID current (T = 4.2 K)

Period = 1.27 T  Loop diameter = 46 nm

Flux noise: $\sqrt{S_\Phi} = 50 \, n\Phi_0/\text{Hz}^{1/2}$
Field noise: $\sqrt{S_B} = 62 \, \text{nT/Hz}^{1/2}$
Spin noise: $\sqrt{S_n} = 0.38 \, \mu_B/\text{Hz}^{1/2}$

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
Sample approach

Bare SQUID on tip

SQUID on tip glued to tuning fork
Figure of merit: Landauer's limit of energy dissipation for irreversible qubit readout

\[ E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J} \]

Qubit at 1 GHz:

\[ P = 40 \text{ fW} \]
Outline

- Introduction
- SQUID-on-tip
- Superparamagnetism in TI
- Thermal nanoscale imaging
Scanning SQUID microscopy methods

Wissberg et al.
Physica C (2017)

Koshnick et al.
APL (2008)

Hasselbach et al.
Dissipation in hBN encapsulated graphene

D. Halbertal et al., Nature 539, 407 (2016)
Dissipation in Graphene – measurement setup

\[ D = 33 \text{ nm} \]
\[ \text{Sens.} = 510 \, \frac{nK}{\sqrt{Hz}} \]
\[ h = 10\text{-}20 \text{ nm} \]
Dissipation in Graphene

$I_{dc} = 3 \, \mu A$, $h= 20 \, \text{nm}$, $V_{bg} = 2 \, \text{V}$
Dissipation by Localized States at Graphene Defects

- Large inelastic $\lambda_{e-ph}$
  - Non-thermalized electrons are everywhere

- Localized states allow electron relaxation

- Defects exist
  - Create localized electronic states
  - States pinned to graphene CNP

Defects
  - Localized states
  - Heat Dissipation by non-thermalized e

Bistritzer & MacDonald, PRL 102 (2009)
Song, Reizer & Levitov, PRL 109 (2012)
Pereira et al., PRL 96 (2006)
González-Herrero et al., Science 352 (2016)
Mao et al., Nat, Phys., 12 (2016)
Static tSOT spectroscopy - experiment

Wehling et al., PRB 80, 85428 (2009)
Dissipation in Graphene – evolution of rings

\( V_{tg} = 0.0 \text{ [V]} \)

\( I_{dc} = 3 \mu A \)

\( h = 20 \text{ nm} \)

\( V_{bg} = 2 \text{ V} \)
Moving tSOT spectroscopy - experiment
Edge defects analysis

\[ \rho = \frac{135 \text{ defects}}{3.5 \mu m} \sim 40 \text{ defects/\mu m} \]
Proliferation of hot electrons

$I_{dc}$

$T_{ac}$ [μK]

-50  0  50

1 μm

500 nm
Single defect spectroscopy – band bending simulation

$V_{tg} = -1.5 \text{ V}$

$V_{bg} = 1 \text{ V}$

$E_D(x)$

$E_F$
\( D_{LS}(E) \)

\( E \) [meV]

\( V_{tg} [V] \)

\( V_{bg} = 0 \) V

\( \delta T \) [a.u.]

\( V_{tg} \) [V]

\( V_{bg} \) [V]
$\delta x$ [nm]

$T_{ac}$ [μK]

$\frac{dV_{bg}}{dx}$

$\delta V_{bg}$

$V_{bg}$ [V]

$I_{dc}$ [μA]

$T_{ac}$ [μK]

$D_{LS}(\epsilon) \propto \delta T(\epsilon)$ [μK]

$\delta E$ [meV]

$\delta x$ [nm]

$\delta V_{bg}$

$\delta x$ [nm]

$\delta V_{bg}$

$\delta x$ [nm]

$\delta V_{bg}$

$\delta x$ [nm]
Scanning SQUID microscopy methods

N. Koshnick et al.
APL 93, 243101 (2008)

K. Hasselbach et al.
SQUID-on-tip fabrication

Ø 1 mm
SQUID-on-tip fabrication

Ø 50 ÷ 400 nm

Al, Nb, Pb, In, Sn
SQUID-on-tip fabrication

Al, Nb, Pb, In, Sn
SQUID-on-tip fabrication

Al, Nb, Pb, In, Sn
SQUID-on-tip fabrication

SC lead → SC lead

SQUID loop → weak links

Al, Nb, Pb, In, Sn
Al SQUID on tip

Pulled quartz tube

Al lead

bare quartz

Al lead

Al lead

quartz

Al lead

SQUID loop

A. Finkler et al., Nano Letters 10, 1046 (2010)
Al SQUID on tip

Quantum interference patterns

SQUID current (T=300 mK)

Period = 60.8 mT  Loop diameter = 208 nm

Flux noise: $\sqrt{S_\Phi} = 2 \mu \Phi_0 / \text{Hz}^{1/2}$

Spin noise: $\sqrt{S_n} = \sqrt{S_\Phi R / r_e} = 65 \mu_B / \text{Hz}^{1/2}$

A. Finkler et al., Nano Letters 10, 1046 (2010)
Pb SQUID on tip

Quantum interference patterns

SQUID current (T = 4.2 K)

Period = 103 mT   Loop diameter = 160 nm

Flux noise: $\sqrt{S_\Phi} = 50 \, \Phi_0/\text{Hz}^{1/2}$
Field noise: $\sqrt{S_B} = 5.1 \, \text{nT}/\text{Hz}^{1/2}$
Spin noise: $\sqrt{S_n} = 1.4 \, \mu_B/\text{Hz}^{1/2}$

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
Pb SQUID on tip

Quantum interference patterns

SQUID current  (T = 4.2 K)

Period = 0.84 T   Loop diameter = 56 nm

Kinetic inductance: $L_k \approx 6 \text{ pH}$
Quantum noise: $\sqrt{S_\Phi} = \sqrt{\hbar L_k} = 12 \text{ n}\Phi_0/\text{Hz}^{1/2}$

Flux noise: $\sqrt{S_\Phi} = 50 \text{ n}\Phi_0/\text{Hz}^{1/2}$
Field noise: $\sqrt{S_B} = 42 \text{ nT}/\text{Hz}^{1/2}$
Spin noise: $\sqrt{S_n} = 0.5 \mu_B/\text{Hz}^{1/2}$

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)


Quantum interference patterns

SQUID current (T = 4.2 K)

Period = 1.27 T
Loop diameter = 46 nm

Flux noise: \( \sqrt{S_\Phi} = 50 \ n\Phi_0/\text{Hz}^{1/2} \)
Field noise: \( \sqrt{S_B} = 62 \ n\text{T}/\text{Hz}^{1/2} \)
Spin noise: \( \sqrt{S_n} = 0.38 \ \mu\text{B}/\text{Hz}^{1/2} \)

D. Vasyukov et al., Nature Nanotech. 8, 639 (2013)
$^3$He scanning SQUID on tip microscope

Piezoelectric coarse X-Y positioners

Sample holder

SQUID on tip and tuning fork assembly

Piezoelectric coarse Z positioner

Piezoelectric X, Y and Z scanners

Figure of merit:
Landauer's limit of energy dissipation for irreversible qubit readout

\[ E = k_B T \ln 2 = 4 \times 10^{-23} \text{ J} \]

Qubit at 1 GHz:
\[ P = 40 \text{ fW} \]
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- 3-junction SQUID-on-tip
- Superparamagnetism in TI
- Thermal nanoscale imaging
Vortices in Pb film

SQUID diameter: 225 nm
Scan area: $12 \times 12 \, \mu m^2$
Pixel size: 100 nm    Scan time: 2 min
$T = 4.2 \, K$
Vortices in Pb film in presence of current

SQUID diameter: 225 nm
Scan area: 12 × 12 μm²
Pixel size: 100 nm Scan time: 2 min
T = 4.2 K B_a = 27 G
Vortex flow in Pb film

\[ I \ (\text{mA}) \]

- \( H_a = 27 \, \text{G} \)
- SOT diameter: 225 nm
- Scan area: 12 \( \times \) 12 \( \mu \text{m}^2 \)
- Pixel size: 40 nm
- Scan time: 4 min/frame
- \( T = 4.2 \, \text{K} \)
Vortex flow patterns

27 G

42 G

90 G

54 G
Pinning and dynamics of a single vortex

DC signal

\[ \mathbf{F}_{\text{ac}} + \mathbf{F}_{\text{dc}} \]

\[ \mathbf{I}_{\text{ac}} + \mathbf{I}_{\text{dc}} \]

AC signal

\[ U(x) = \frac{-U_0}{1 + \left(\frac{x}{\xi}\right)^2} \]

- Potential
- \( \xi \) - core size
- \( x_{\text{ac}} \) - ac displacement

Pb film

\[ \xi = 46.4 \text{ nm} \]
\[ \lambda = 90 \text{ nm} \]
\[ d = 75 \text{ nm} \]
\[ T = 4.2 \text{ K} \]

L. Embon et al., Scientific Reports 5, 7598 (2015)
Single vortex dynamics

\[ F_{ac} + F_{dc} \]

\[ I_{ac} + I_{dc} \]
Vortex trajectory

L. Embon et al., Scientific Reports 5, 7598 (2015)
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