Nanoscale thermal imaging of dissipation in quantum systems and in encapsulated graphene

Dorri Halbertal (Weizmann Institute of Science)

L. Embon, N. Shadmi, Y. Anahory, HR Naren, J. Sarkar, A. Uri, K. Bagani, A. Y. Meltzer, Y. Ronen, Y. Myasoedov, E. Joselevich, E. Zeldov

M. Ben-Shalom, J. Birkbeck, A. K. Geim

L. S. Levitov

J. Cuppens
Dissipation: Agent of change
Talk Outline

- SQUID-on-tip Thermal imaging
- Warm up example
- Graphene
SQUID-on-tip fabrication

Ø 1 mm
SQUID-on-tip fabrication

Ø 30 ÷ 300 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

Side view

Bottom view

SC lead → SC lead

SQUID loop

weak links

Al, Nb, Pb, In, Sn

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Invited presentation ED4-5-INV was given at ISS 2017, December 13-15, 2017, Tokyo, Japan.
SQUID on tip

- SC lead → SC lead
- SQUID loop → weak links

Al, Nb, Pb, In, Sn

Loop diameter = 46 nm
 Flux noise: $\sqrt{S_\Phi} = 50 \, n\Phi_0/Hz^{1/2}$
 Spin noise: $\sqrt{S_n} = 0.38 \, \mu_B/Hz^{1/2}$

Vasyukov et al., Nat. Nano. (2013)
Recent studies: Scanning Nano-SQUID on Tip

Vortex dynamics in superconductors

Scientific reports (2015)
Nature Communications (2017)

Superparamagnetic dynamics in magnetic TIs

Science advances (2015)

Emergent nanoscale superparamagnetism at oxide interfaces

Nature Communications (2016)
Thermal and Magnetic Sensitivity

Magnetic sensitivity

Thermal sensitivity

Cold amplifier

$T \text{ [K]}$
Origin of thermal sensitivity

Thermal response:
- $I_{SOT} = 9.5 \mu A/K$
- $tSOT @ 4.2 K$

Current noise:
- $S_I^{1/2} = 8.3 \text{pA/Hz}^{1/2}$

Thermal noise:
- $S_T^{1/2} = 870 \text{nK/Hz}^{1/2}$

D. Halbertal, et al. Nature 539, 407 (2016)
Thermal coupling to sample

- Plasmon TEM
- SNOM
- TC SThM
- Res. SThM
- Raman
- nanodiamond

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

- $R_{sens-support} \gg R_{sens-dev} \gg R_{dev-sub}$
- $R_{sensor-support} \approx 10^{11} K/W$
- $R_{sensor-device} \approx 10^{8} - 10^{10} K/W$
- $R_{device-substrate} \approx 10^{7} K/W$

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:

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

D. Halbertal, et al. Nature 539, 407 (2016)
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Dissipation in Carbon Nanotubes

SEM

$I_{ac}=12 \text{ nA}$

$T_{ac} [\mu K]$

$T_{ac} [mK]$

$T_{ac} [\mu K]$

$T_{ac} [\mu K]$

$T_{ac} [mK]$

Woodside and McEuen, *Science* 296, 2002

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Halbertal et al. *Nature* 539, 407 (2016)

Woodside and McEuen, *Science* 296, 2002

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Dissipation in hBN encapsulated graphene

D. Halbertal, et al. Nature 539, 407 (2016)
Dissipation in graphene – evolution of rings

Vacancies and adatoms form localized states near Dirac point in graphene

$D_{\text{ac}} = 3 \mu\text{A}$
$h = 20 \text{nm}$
$V_{bg} = 2 \text{V}$
$T = 4.2 \text{ K}$

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)

Atomic source of phonons

D. Halbertal, et al. Science 358, 1303 (2017)
Resonant inelastic scattering by a single localized state

D. Halbertal, et al. Science 358, 1303 (2017)
Moving tSOT spectroscopy - experiment

$V_{bg} = 2.00 \text{ [V]}$

$V_{tg} = 4.20 \text{ [V]}$

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

$\delta \epsilon = 13 \text{ meV}$

Empty state

Occupied state

D. Halbertal, et al. Science 358, 1303 (2017)
Summary

Nanoscale thermal imaging of quantum systems with sub 1 µK sensitivity

Dissipation dominated by edge defects in graphene

Inelastic electron scattering by a resonant localized state

Spectroscopy of localized states

Dissipation in quantum dots in CNT

Detection of phonon emission from a single atomic defect