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Graphene-Superconductor Hybrid Devices

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THE RESEARCH FOUNDATION OF STATE UNIVERSITY OF NEW YORK

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Final Report

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14. ABSTRACT
This project studies the physics and application of the graphene-superconductor hybrid devices. The research work focuses on two aspects: 1) understanding the intrinsic superconducting proximity effect of Dirac electron in graphene; 2) developing novel graphene-superconductor devices for exploring of fundamental science and for frontier technology/applications.
1. We have a devised novel technique which allows fabrication of ultra-high-quality suspended graphene Josephson weak links. With these devices, we demonstrated the signature of the long-standing theoretical prediction of the evanescent charge transport near the Dirac point.
2. We carried out a comprehensive study of the impact of low magnetic field on Andreev reflection at the graphene-superconductor interface. Andreev reflection suppression in low magnetic fieldis found to be strongly affected by the effective superconducting gap at the graphene-superconductor interface and the Abrikosov vortex dynamics.
3. In ultrahigh quality suspended graphene Josephson weak links, which shows well developed quantum Hall plateaus in magnetic field down to ~0.1Tesla, we observed strong suppression of Andreev reflection at the quantum Hall regime. We have devised a new device scheme which couples superconductivity to a quantum Hall antidot in graphene. In our preliminary work on such device, we have been able to localize quantum Hall edge states in such antidot, and demonstrate Aharonov Bohm conductance oscillations.

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FINAL PERFORMANCE REPORT

Graphene-Superconductor Hybrid Devices

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Xu Du
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This project studies the physics and application of the graphene-superconductor hybrid devices. The research work focuses on two aspects: 1) understanding the intrinsic superconducting proximity effect of Dirac electron in graphene; 2) developing novel graphene-superconductor devices for exploring of fundamental science and for frontier technology/applications.

1) **Intrinsic superconducting proximity effect of Dirac electrons.**

We have a devised novel technique which allows fabrication of ultra-high-quality suspended graphene Josephson weak links. Our Nb-graphene-Nb devices show mobility above 300,000 cm^2/Vs, minimum carrier density tunable down to ~10 electrons in the graphene channel, and with transparent graphene/Nb interface which supports Josephson current. With these devices, we demonstrated the signature of the long-standing theoretical prediction of the evanescent charge transport near the Dirac point.

The ultrahigh quality of our graphene-superconductor weak links opens the possibility for studying the interplay between superconducting proximity effect and quantum magnetotransport (e.g., quantum Hall effect). We carried out a comprehensive study of the impact of low magnetic field on Andreev reflection at the graphene-superconductor interface. Various interface compositions, including Graphene-Ti/Au-Nb, Graphene-Ti/Pd-Nb, Graphene-V-Nb, and Graphene-Ti-Nb, and Graphene-Ti/Pd-NbN had been studied. Andreev reflection suppression in low magnetic field $B << B_{C2}$ (B_{C2} being the upper critical field of the superconducting leads) is found to be strongly affected by the effective superconducting gap at the graphene-superconductor interface and the Abrikosov vortex dynamics.

Through our study on magnetic suppression of Andreev reflections in diffusive graphene-superconductor junctions, we have established the technique for making such devices which allows Andreev reflection to persist up to the upper critical magnetic field. The same technique was applied to ultrahigh quality suspended graphene Josephson weak links, which shows well developed quantum Hall plateaus in magnetic field down to ~0.1Tesla. In wide graphene devices where the two chiral edge states are well separated, we observed strong suppression of Andreev reflection at the quantum Hall plateaus, which is very different from that in diffusive devices. This suppression of Andreev reflection in the quantum regime is attributed to the fact that Andreev reflection cannot couple the two chiral edges which are far separated.

We have then devised a new device scheme which couples superconductivity to a quantum Hall antidot in graphene. In this set up the two quantum Hall edges which make up the two halves of the antidot are closely placed and can be conveniently coupled through Andreev conversion. Our preliminary work on such device focused on studying the spectrum of energy quantization in the antidot in the quantum Hall regime. We have been able to localize quantum Hall edge states in such antidot, and demonstrate Aharonov Bohm conductance oscillations.

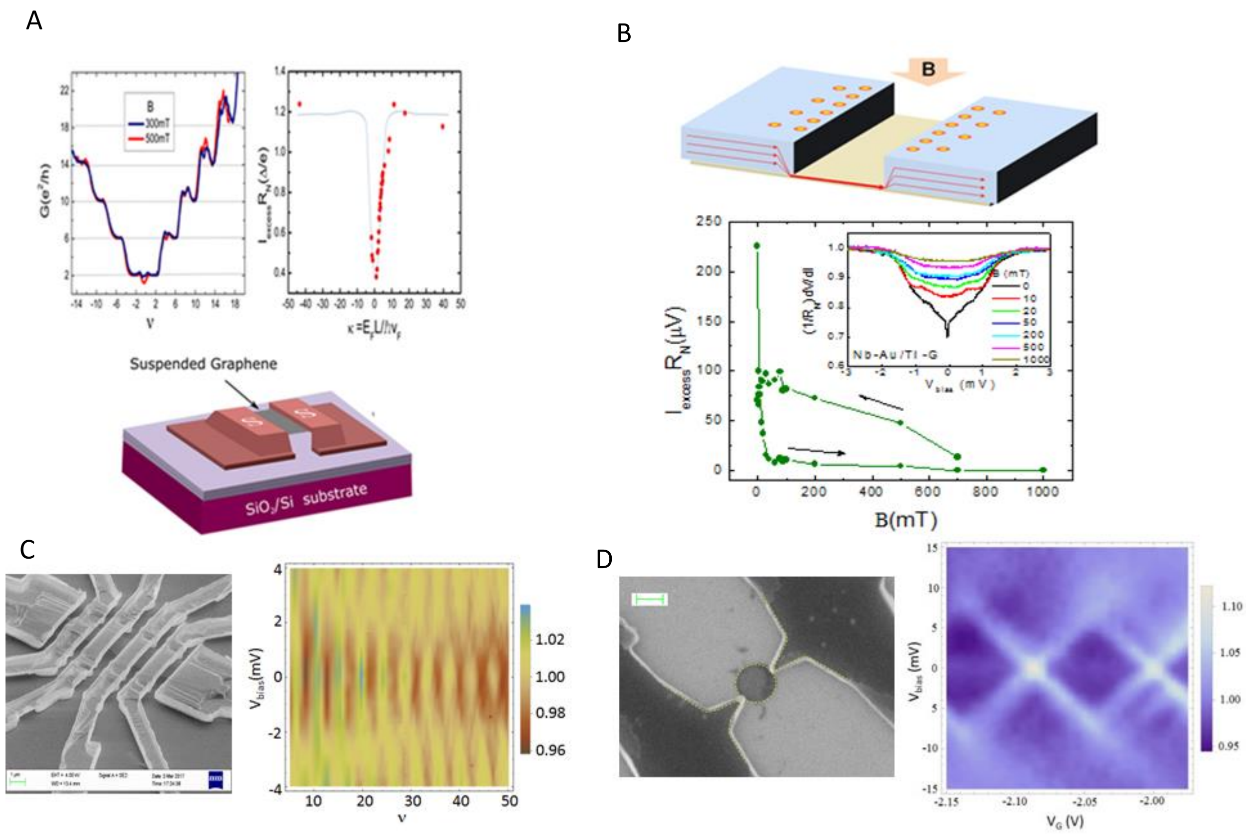

Figure 1. A. Suspended graphene Josephson weak links. High quality is indicated by the well-developed quantum Hall plateaus at 0.3T. Near Dirac point, signature of evanescent transport is observed as a sharp reduction of the normalized excess current. B. Graphene-superconductor weak links in magnetic field. Vortices pile up at the superconductor edges where current bunches in/out of graphene. The Andreev reflection process is strongly affected by the amplitude of the magnetic field (bottom panel inset, for a graphene-Ti/Au-Nb Josephson weak link) as well as vortex dynamics (bottom panel, for a graphene-Ti/Pd-NbN Josephson weak link). C. Suspended Graphene-Nb weak links in quantizing magnetic field. The surface plot shows the dV/dI as a function of filling factor and bias voltage. D. Graphene quantum Hall antidot, coupled to Nb leads through point-contacts. The right panel shows the bias and gate voltage dependence of the differential conductance (charge stability plot), where Coulomb diamonds and excited states are clearly visible.

2). Novel graphene-superconductor devices.

We have developed the scheme of graphene superconducting tunneling junction (GSTJ) bolometers (which we pioneered through our previous AFOSR supported work). The basic principle of GSTJ bolometer is to use the electron gas in graphene as a radiation absorber and use the tunneling resistance of the superconducting tunnel junction (STJ) as an electron temperature thermometer. The superconducting leads provide thermal confinement to the hot electrons inside the absorber, lowering the thermal conductance and optimize the sensitivity. Using TiOx as tunnel barrier, the large tunneling capacitance enables low microwave impedance while keeping a large DC resistance which cuts down the out-diffusion of hot electrons. With a high frequency impedance that is very close to 50Ω, our antenna-coupled device shows high microwave efficiency. Experimental characterization of the GSTJ bolometers were carried out using Nb and NbN as superconducting leads, at liquid helium temperature using radio frequency radiation. Our experiments focused on characterization of electron-phonon coupling (the dominating cooling mechanism). Based on our experimental results at liquid helium temperature, we have carried out simulations which optimize the performance of these devices as power sensors and single photon detectors in the millikelvin temperature regime. Our work provided useful guidance to the development of graphene-based bolometers.

Besides conventional superconductors, we have also explored combing high Tc superconductivity with the exceptional and tunable electronic properties of graphene. Experimentally a major challenge is to form a well-defined and clean interface between the two materials. We have applied the co-lamination technique to overlay graphene with layered High Tc material BSCCO, avoiding lithography which degrades the interface. In our devices, we observed superconducting tunneling behavior with relatively large (usually >~100kΩ/μm^2) interfacial resistance. The resistive interface suggests intrinsically weak coupling between graphene and BSCCO. Further work will be focused on the possibility of improving the coupling strength through pressure/strain.

From our work on combing graphene with BSCCO, it becomes evident that BSSCO, as well as many of the newly studied 2D materials, are not sufficiently stable for the conventional nano-lithography process. This led us to explore the possibility of "mechanically assemble" 2D crystals onto predefined superconducting leads. A systematic study was carried out to characterize the interface transparencies in junctions created by directly transferring/pressing various 2D crystals onto Au(~4nm)-coated Nb leads. We show that mechanically assembled interfaces can have equal or even better transparency compared to those fabricated through conventional nano-lithography. This opens up the possibility of combing superconductivity with a wide spectrum of novel 2D materials, which may not be chemically stable. We also identified the major bottle-neck of the interface quality in such mechanically assembled junctions to be the surface roughness of the leads.

Another category of experiments on graphene aims to combine superconductivity with the mechanical motion which is conveniently achievable in our suspended device geometry. We have carried out fabrication and nanoelectromechanical characterization of tunable graphene resonators, which are based on suspended graphene field effect transistors on flexible polyimide substrate. We have studied the non-linear dynamics of the mechanical vibration in these devices. In addition, through substrate bending we could tune the strain and the surface wrinkling in graphene, and correlate the wrinkle-induced random gauge field with the transport signatures on charge carrier scattering.

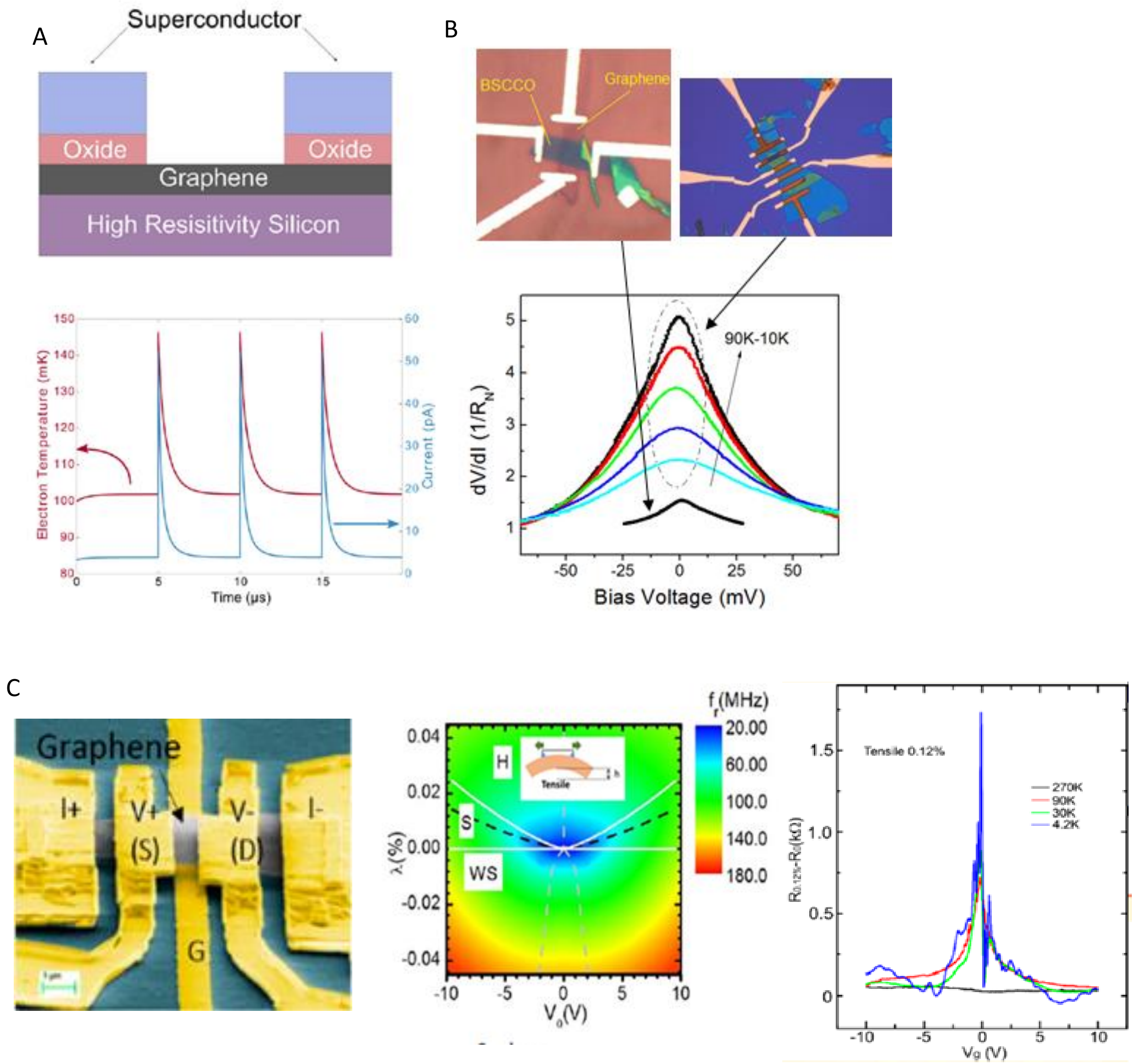

Figure 2. A. Graphene-superconductor tunnel junction bolometer. The bottom panel shows the simulated single THz phonon response at a base temperature of 100mK. B. Graphene-BSCCO and BSCCO-BSCCO overlap junctions fabrication through co-lamination. The bias dependence of differential resistance shows quasiparticle tunneling behavior. Note that the quasiparticle tunneling curve for BSCCO/BSCCO junction is broader than that for graphene/BSCCO because the associated energy gap is 2Δ as opposed to Δ. C. Left panel: false color SEM image of a suspended graphene nanoelectromechanical resonator. Middle panel: Strain and gate tuning of resonance frequency. Right panel: Strain-induced resistance from random wrinkle scattering in graphene, at various temperatures.

Preprints Under Review

Contact transparency in mechanically assembled 2D material devices
Scott Mills, Naomi Mizuno, Peng Wang, Jian Lyu, Kenji Watanabe, Takashi Taniguchi, Liyuan Zhang, Xu Du

Quantum Hall Antidot in Graphene-Based van der Waals Heterostructure
Scott Mills, Anna Gura, Kenji Watanabe, Takashi Taniguchi, Matthew Dawber, Dmitri Averin and Xu Du

Publications

- Random gauge field scattering in mono-layer graphene
Fen Guan and Xu Du, to appear in Nano Letters

- Magnetic field suppression of Andreev conductance at superconductor–graphene interfaces
Piranavan Kumaravadivel, Scott Mills, and Xu Du, 2D Materials Volume 4, Number 4, 2017

-Signatures of evanescent transportin ballistic suspended graphenesuperconductor junctions
Piranavan Kumaravadivel and Xu Du, Nature Scientific Reports | 6:24274 | DOI: 10.1038/srep24274

-Tuning strain in flexible graphene nanoelectromechanical resonators
Fen Guan, Piranavan Kumaravadivel, Dmitri V. Averin, and Xu Du, Applied Physics Letters **107**, 193102 (2015); doi: 10.1063/1.4935239

-Ultrasensitive Graphene Far-Infrared Power Detectors

C.B. McKitterick, D.E. Prober, H. Vora, and X. Du, J. Phys. Condens. Matter 27 164203 (2015)

-Graphene-based Bolometers
Xu Du, Daniel E. Prober, Heli Vora, Christopher B. Mckitterick. Graphene and 2D materials, Volume 1, Issue 1, ISSN (Online) 2299-3134, DOI: 10.2478/gpe-2014-0001, (2014)

-Graphene microbolometers with superconducting contacts for terahertz photon detection
Christopher B. McKitterick, Heli Vora, Xu Du, Boris S. Karasik, Daniel E. Prober, Journal of Low Temperature Physics, DOI: 10.1007/s10909-014-1127-3 (2014)

-Nonlinear vs. bolometric radiation response and phonon thermal conductance in graphene-superconductor junctions
Heli Vora, Bent Nielsen and Xu Du, Journal of Applied Physics, 115, 074505 (2014)

Presentations

-Suspended Graphene Weak-Links in Magnetic Field, March Meeting 2017

-Probing the Graphene Bridges, Dept. of Physics, South University of Science and Technology, P. R. China, Oct. 2016

-Graphene-superconductor devices, Air Force Office of Scientific Research, Arlington VA, Nov. 2016

-Probing the Graphene Bridges, 2D and Dirac materials workshop, Jacksonville, Dec. 2016

-Probing the Graphene Bridges, Peking University 2015

-Probing the Graphene Bridges, AFOSR 2015

- Graphene-Superconductor Junctions, Penn State University, 2014

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The AFOSR Program Officer currently assigned to the award

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Abstract

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Addressing the above accomplishments, 8 research papers were published and 2 preprints are under reviewe. 7 presentations were given which are related to the funded work.

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Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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