REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 17-11-2017	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 19-Aug-2013 - 18-Aug-2017

4. TITLE AND SUBTITLE
Final Report: Physics-Quantum Information Science: Quantum Limited Electrometry and Ultra-Strong Photon-Phonon Coupling using a Cavity-Embedded Single Cooper Pair Transistor

5a. CONTRACT NUMBER
W911NF-13-1-0377

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Dartmouth College
11 Rope Ferry Rd.

Hanover, NH 03755 -1404

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
62403-PH.4

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Alexander Rimberg
UU	UU	UU	UU		19b. TELEPHONE NUMBER 603-646-6569

RPPR Final Report
as of 21-Mar-2018

Agency Code:

Proposal Number: 62403PH **Agreement Number: W911NF-13-1-0377**
INVESTIGATOR(S):

Name: Alexander J Rimberg ajrimberg@
Email: Alexander.J.Rimberg@Dartmouth.edu
Phone Number: 6036466569
Principal: Y

Organization: **Dartmouth College**
Address: 11 Rope Ferry Rd., Hanover, NH 037551404
Country: USA
DUNS Number: 041027822 EIN: 020222111

Report Date: 18-Nov-2017 Date Received: 17-Nov-2017
Final Report for Period Beginning 19-Aug-2013 and Ending 18-Aug-2017
Title: Physics-Quantum Information Science: Quantum Limited Electrometry and Ultra-Strong Photon-Phonon Coupling using a Cavity-Embedded Single Cooper Pair Transistor
Begin Performance Period: 19-Aug-2013 **End Performance Period:** 18-Aug-2017
Report Term: 0-Other
Submitted By: Alexander Rimberg Email: Alexander.J.Rimberg@Dartmouth.edu
Phone: (603) 646-6569
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 2

Major Goals: Over the past several years, techniques for probing and controlling the quantum state of electrical and mechanical devices have undergone rapid development. Here, we propose to use these techniques for the sensing of electrical charge and the detection of mechanical motion.

Our experimental scheme is based on embedding a Cooper pair transistor (CPT) in a superconducting microwave cavity. In our arrangement the quantum inductance of the CPT causes a shift in the resonant frequency of the cavity containing it. Since the quantum inductance is charge dependent, this allows us to harness the extreme charge sensitivity of the CPT to perform dispersive, and in principle quantum limited, measurements of electrical charge.

In our proposed research, we will investigate the charge sensitivity of a cavity-embedded CPT and probe the limits of charge sensitivity possible with this approach. In particular, we will determine if this charge detection technique offers an advantage in sensitivity over existing techniques, such as the radio-frequency single- electron transistor. We will also attempt to determine if the charge sensitivity is limited by fundamental noise sources such as photon shot noise, or sample-specific sources such as 1/f charge noise. We will investigate the use of parametric pumping of the cavity for improved cCPT performance. Time permitting, we will also investigate the quantum mechanical backaction of the cCPT by coupling it to a nanomechanical resonator, allowing dispersive measurement of the resonator position.

Accomplishments: See PDF in the "Upload" section.

Training Opportunities: During the course of this grant, there have been multiple opportunities for training for two graduate students, Juliang Li and Bhargava Thyagarajan, and for one postdoc, Joel Stettenheim.

All of the personnel above have had a chance to develop strong skills in many nanoscale fabrication techniques, in particular electron beam lithography. Other fabrication skills they have developed include thin film deposition, reactive ion etching, photolithography, and atomic force microscopy.

One of the graduate students, Juliang Li, also developed experience using Sonnet for microwave cavity design, and the various fabrication techniques needed to produce superconducting microwave cavities, including deposition, pattering and etching of Nb films.

Joel and Bhargava have also developed additional fabrication skills, in particular fabrication of nanomechanical resonators out of SiN, including lithography, patterning, and release.

Both Joel and Juliang have developed significant expertise with operation of cryogenic instruments, in particular both He-3 and dilution refrigerators. They both have gained experience in low noise electrical and microwave measurements; in addition, Juliang has expertise in operation of ultra-low-noise SLUG and Josephson parametric amplifiers, and in the microwave measurement techniques needed to characterize them.

Results Dissemination: Our results have been disseminated to the scientific community through publishing of papers, and presentation of results at conferences, either as a talk or a poster.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Alexander Jesse Rimberg
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Juliang Li
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Bhargava Thyagarajan
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Joel Stettenheim
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Final Report 2017

During the last year of support from this grant, we have returned to making rapid progress on our goals of demonstrating ultra-sensitive charge detection with a cavity-embedded Cooper pair transistor (cCPT) and using the cCPT to promote ultrastrong coupling between cavity photons and a nanomechanical resonator (NR).

Using internal support from Dartmouth, the PI's students travelled to the Center for Nanoscale Systems at Harvard to make use of electron-beam lithography (EBL) facilities there while a new EBL facility was being installed at Dartmouth. Using the CNS facility, and superconducting microwave cavities developed previously through this grant, graduate student Juliang Li successfully produced a cCPT with charging and Josephson energies close to our target values. This sample was placed in one of our dilution refrigerators, and measured with an amplifier chain consisting of an ultra low noise SLUG amplifier from the McDermott group at the University of Wisconsin, followed by a HEMT amplifier from Low Noise Factory. This sample has provided us with our first real opportunity to evaluate the cCPT as an ultrasensitive, low power charge detector.

Our first characterization of the cCPT consisted of measurements of the cavity resonance frequency shift versus both gate charge and flux bias; results of these measurements are shown in Fig. 1. Here, we measure the power reflected from the cCPT versus gate charge n_g and frequency for different dc external flux Φ_{dc}. The spectra are fully $2e$ periodic, with no sign of quasiparticle poisoning. Comparing our results to a numerically calculated five-charge-state model of the cCPT Hamiltonian, we find excellent agreement using $E_c/h = 42\,\mathrm{GHz}$ and $E_J/h = 20\,\mathrm{GHz}$, in agreement with expected junction sizes and resistances. These results provide very strong evidence that we can use both n_g and Φ_{dc} to control our CPT, thereby tuning its quantum properties, for example its inductance, that are determined by the CPT band structure. The results also demonstrate that our Hamiltonian accurately describes the cCPT band structure, and suggest that it should in fact be possible to operate it as an ultrasensitive dispersive charge detector, as expected.

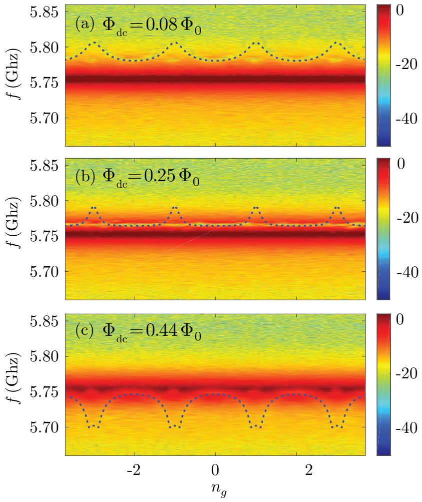

Figure 1: False-color images of microwave power reflected from a cCPT vs. frequency and gate charge for various Φ_{dc}: (a) $\Phi_{\mathrm{dc}} = 0.08\Phi_0$, (b) $0.25\Phi_0$ and (c) $044\Phi_0$. Dashed blue lines are fits to a five-charge state model.

Based on our knowledge of the cCPT Hamiltonian, we also expect that it should act as a degenerate parametric amplifier/oscillator, due to the nonlinearity of the cCPT band structure as a function of both n_g and external flux Φ_{dc}. We have verified this expectation by pumping the external flux at twice the cavity resonant frequency, and measuring the output power of the cavity for differing pump powers. Results of this measurement can be seen in Fig. 2, which shows the output power at the cavity resonance frequency ω_0 for a flux pump at $2\omega_0$. Even in the absence of an input signal, the cavity produces photons at ω_0, indicating operation as a parametric oscillator. Furthermore, the insets to Fig. 2(a) and (b) show that we obtain a parametric gain of up to 15 dB, and that the output microwaves are squeezed. From these measurements and recent calculations performed by Miles Blencowe, we estimate a very large parametric coupling strength $\chi \approx 100$MHz.

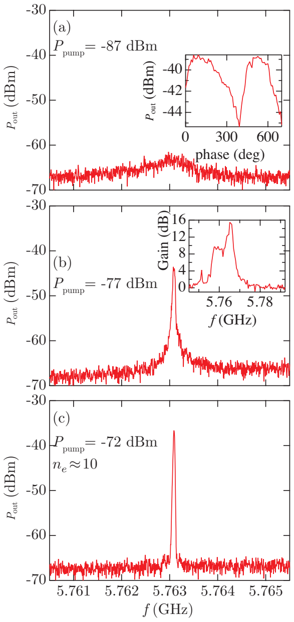

Figure 2: Photon emission from a cCPT pumped by an external magnetic flux at frequency $\omega_p = 2\omega_0$, for different pump powers (a) −87 dBm, (b) −77 dBm and (c) −72 dBm.

To illustrate the utility of flux pumping for charge detection, we show in Fig. 3 the response of the cCPT to charge modulation at different bias points. Both a carrier wave and flux pump were applied, giving rise to a total of roughly 300 total cavity photons. The appearance of multiple sidebands even for very small charge excitations as in Fig. 3(a) is a consequence of the dispersive nature of the charge detection process: we are performing phase modulation of the signal rather than amplitude modulation. For these measurements we estimate a *world record* charge sensitivity of $1.8 \times 10^{-7}\ e/\sqrt{\text{Hz}}$, nearly an order of magnitude better than the previous world record $9 \times 10^{-7}\ e/\sqrt{\text{Hz}}$ while using *approximately 1,000 times fewer cavity photons*. This result also far surpasses previous dispersive charge detection results for which the best reported charge sensitivity is on the order of $1 \times 10^{-5}\ e/\sqrt{\text{Hz}}$.

Finally, we have made great strides toward our goal of coupling a cCPT to a nanomechanical resonator. Using the facilities at Harvard, we have successfully produced test cCPT/NR structures in a superconducting microwave cavity. The structures consist of a cCPT with a roughly 10 μm long island coupled to a SiN nanoresonator of similar length, with a width of about 100 nm and an overall thickness of about 150 nm, including metallization. We are in the process of tuning the CPT junction resistances and areas in similar samples, so that we can achieve charging and Josephson energies close to those for the cCPT described earlier. We expect that a working sample

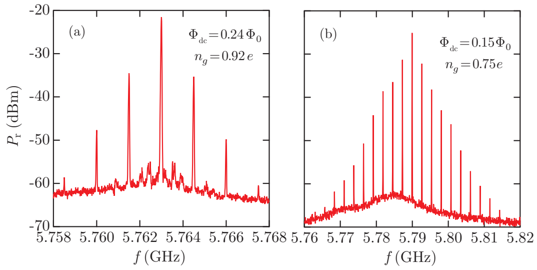

Figure 3: Charge modulation sidebands for the cCPT at two different bias points. The modulation frequencies and amplitudes are 1.5 MHz (2.7 MHz) and $7 \times 10^{-3}e$ ($3.5 \times 10^{-2}e$) for (a) and (b) respectively.

will be produced in the near term (within a few weeks to a month of this writing), allowing us to evaluate use of the cCPT for ultrasensitive position detection and coupling of the NR to cavity photons.

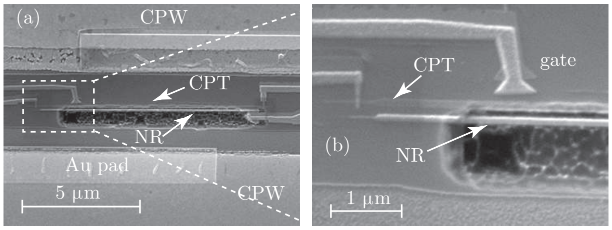

Figure 4: (a) Electron micrograph of a cCPT coupled to a SiN mechanical nanoresonator, all embedded in a Nb coplanar waveguide cavity. The CPT, NR, CPW cavity, and Au contact pads are all indicated. (b) Detail of the CPT and NR, showing the Josephson junctions, released NR, and CPT gate.