様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Detection of quantum states of single electrons on liquid helium

研究課題名（英文）Detection of quantum states of single electrons on liquid helium

研究代表者
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研究者番号：７０８６６７４８

交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：本プロジェクトでは、単一電子の量子状態検出の感度と帯域幅を大幅に向上させる二段階の低温増幅方式を開発しました。この方法は、100 kHzから100 MHzの周波数範囲で40 dBの一定ゲインを達成し、リュードベリ状態の正確な検出を可能にしました。

この進展により、量子コンピューティングの重要な課題に対処し、より効率的で高密度な量子ビットアレイの実現に寄与します。また、高感度な低温測定を必要とする天体物理学や材料科学などの分野にも広く応用可能です。

研究成果の学術的意義や社会的意義
This research enhances quantum states detection, crucial for scalable quantum computing, addressing major scientific challenges. It also benefits fields requiring high-sensitivity low-temperature measurements, such as astrophysics and materials science, driving scientific and technological progress.

研究成果の概要（英文）：Our project successfully developed a two-stage cryogenic amplification scheme, significantly enhancing the sensitivity and bandwidth of quantum state detection for electrons on liquid helium. This method achieved a constant gain of 40 dB over a frequency range of 100 kHz to 100 MHz, enabling the accurate detection of Rydberg states.
This advancement addresses critical challenges in quantum computing, paving the way for more efficient and densely packed qubit arrays. Additionally, the improved detection methods have broader applications in fields requiring high-sensitivity measurements at low temperatures, such as astrophysics and material science. The project's findings contribute significantly to the development of scalable quantum computers and other advanced technologies.

研究分野：cryogenic and superconducting electronics

キーワード：Cryogenic amplifer　Electrons on Helium　Qubits readout　Cryogenic electronics

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Quantum computing is poised to revolutionize various fields by performing complex computations far beyond the capabilities of classical computers. This revolutionary potential stems from quantum bits (qubits) leveraging quantum superposition and entanglement, enabling exponentially greater computational power. The development of practical quantum computers hinges on the ability to reliably read out and manipulate qubits. Among various qubit platforms, surface electrons on liquid helium (SELH) stand out due to their exceptionally high electron mobility and minimal environmental noise, making them ideal for quantum computing applications.
Despite these advantages, the practical use of SELH has been limited by significant challenges in detecting quantum states of single electrons. Existing methods have struggled with sensitivity and scalability, impeding progress toward practical SELH-based quantum computing. This project aimed to address these challenges by developing advanced detection and manipulation techniques for single-electron quantum states on liquid helium, thus contributing significantly to the field of quantum computing.

２．研究の目的

The primary objective of this project was to enhance the detection and manipulation of quantum states in single electrons on liquid helium. This involved:
・Implementing Cryogenic Amplification: Employing an advanced amplification scheme to minimize noise and improve signal fidelity.
・Developing High-Sensitivity Detection Methods: Utilizing advanced nanofabrication techniques to create devices capable of detecting quantum states with high sensitivity.
・Exploring Quantum State Manipulation: Designing micro-resonators for the precise manipulation of quantum states, facilitating the development of scalable quantum computing architectures.
These advancements were expected to overcome existing limitations in SELH qubit technology, paving the way for more efficient and scalable quantum computers.

３．研究の方法

·Cryogenic Amplification:
To enhance the sensitivity and bandwidth of quantum state detection, the project successfully implemented a two-stage cryogenic amplification scheme. The first stage involves a home-made heterojunction bipolar transistor (HBT) amplifier placed close to the signal source to reduce parasitic capacitance and noise. This stage operates at low power dissipation (approximately 90 μW) and is located at the still plate of a dilution refrigerator. The second stage utilizes a commercial cryogenic amplifier (CMT-CITLF1) positioned at the 4-K plate, providing a high gain of 40 dB over a wide frequency range (100 kHz – 100 MHz).
·Nanofabrication:
The project aimed to leverage state-of-the-art nanofabrication techniques to develop high-sensitivity detection devices. The primary focus was on creating radio-frequency single-electron transistors (rf-SETs) using electron-beam lithography and shadow evaporation techniques. These devices are crucial for detecting the quantum states of single electrons with unprecedented sensitivity. However, due to limited time and resources available to the Principal Investigator (PI) following a change in research role, these steps could not be completed as planned.
The project also aimed to explore the use of micro-resonators for manipulating quantum states. These resonators were to be fabricated using microfabrication techniques and designed to achieve localized excitation of single electrons without affecting neighboring qubits. However, due to the same constraints of time and resources, this aspect of the project could not be completed within the project period.

４．研究成果

·Detection Method:
The project successfully developed and implemented a two-stage cryogenic amplification scheme (Figs. 1a and 1b). This method significantly improved the sensitivity and bandwidth of quantum state detection. Figures 2a and 2b show the difference in sensitivity between amplified measurements using one-stage versus two-stage methods, achieving a constant gain of 40 dB over the frequency range of 100 kHz to 100 MHz. Notably, without amplification, the signal cannot be detected with a voltage measuring lock-in amplifier. This advancement enables the accurate detection of Rydberg states of single electrons on liquid helium.
Experimental Validation: The enhanced detection method was experimentally validated, demonstrating effective readout of Rydberg states. This validation confirms the feasibility of using SELH for practical quantum computing applications.

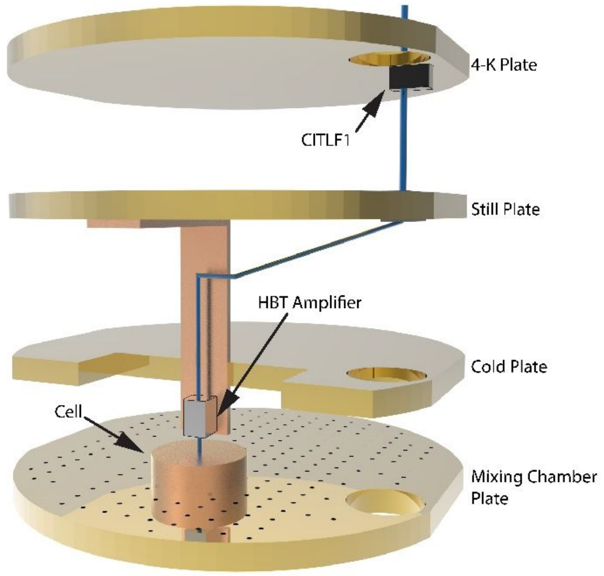
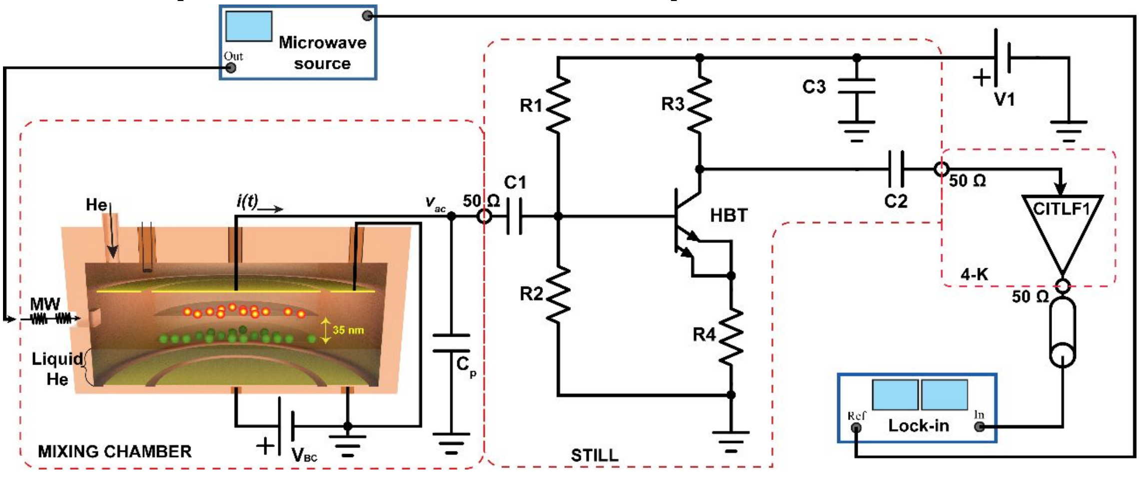


Fig. 1: a) Schematics of the experimental setup for the two-stage amplification showing the first-stage HBT amplifier attached to the still plate by a copper link, and a commercial amplifier (CITLF1) attached to the 4-K plate.



b)Two-stage amplifier circuit. The image-charge signal *Vac* due to pulsed MW-excited SE is capacitively coupled to and amplified by a two-stage amplification scheme (HBT+CITLF1). The amplified signal is measured at the room temperature using a conventional lock-in amplifier that is referenced by the modulation frequency of the pulsed MW-excitation.

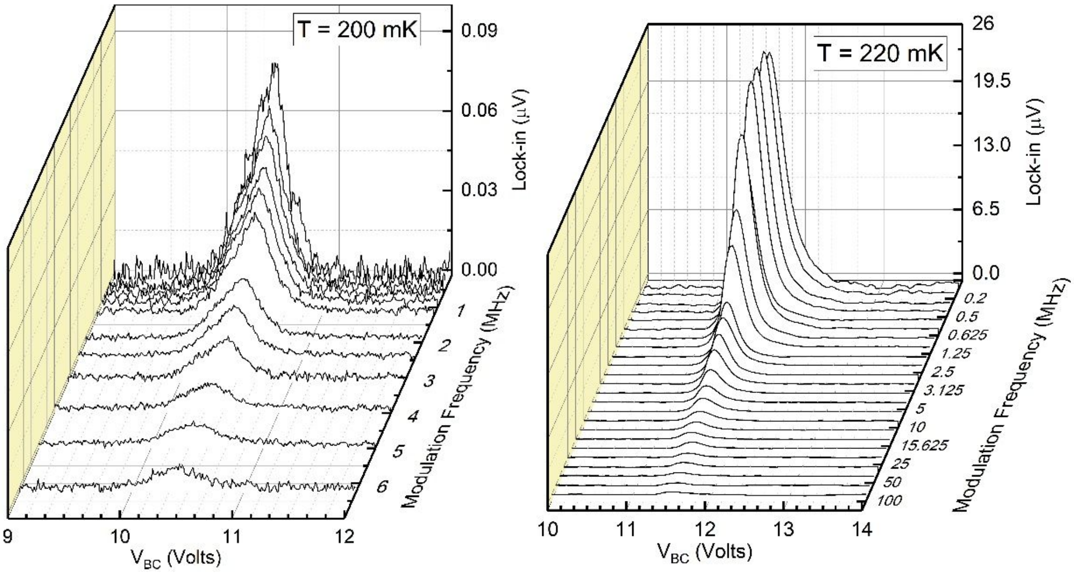


Fig.2 a)(right)Voltage signal amplified by the two-stage amplifiers and measured by the lock-in amplifier for SE at T = 220 mK for different modulation frequencies of the applied pulse-modulated MW. b) (left) Voltage signal amplified by only the HBT-based amplifier measured by the lock-in amplifier for SE at T = 200 mK for different modulation frequencies at similar MW frequency.

·Possible Impact

Quantum Computing: The project's advancements address critical scalability challenges in quantum computing. By enabling the accurate detection and manipulation of quantum states in electrons on liquid helium, the project paves the way for more efficient and densely packed qubit arrays.

Broader Applications: Beyond quantum computing, the improved detection methods and cryogenic amplification techniques have broader applications in fields requiring high-sensitivity measurements at low temperatures. Potential applications include astrophysics, material science, and other areas where precise detection of small signals is essential.

·Unanticipated Findings

Enhanced Stability: An unexpected yet significant outcome of the cryogenic amplification scheme was the enhanced stability of the measurement system. The low-power dissipation and effective noise reduction contributed to reducing thermal fluctuations and environmental noise, thereby improving the overall reliability of the detection method.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Elarabi Asem、Kawakami Erika、Konstantinov Denis	４．巻 202
２．論文標題 Cryogenic amplification of image-charge detection for readout of quantum states of electrons on liquid helium	５．発行年 2021年
３．雑誌名 Journal of Low Temperature Physics	６．最初と最後の頁 456～465
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10909-020-02552-w	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Kawakami Erika、Elarabi Asem、Konstantinov Denis	４．巻 126
２．論文標題 Relaxation of the Excited Rydberg States of Surface Electrons on Liquid Helium	５．発行年 2021年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 106802-1~5
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.126.106802	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計1件（うち招待講演　0件／うち国際学会　1件）

１．発表者名 Asem Elarabi
２．発表標題 Image-charge spectroscopy of the Rydberg states of surface electrons on liquid helium
３．学会等名 EIH2020（国際学会）
４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	コンスタンチノフ　デニス (Konstantinov Denis)	沖縄科学技術大学院大学・量子ダイナミクスユニット・PI	

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関