論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Study on Transport Properties of Single-Molecule and Single-Quantum-Dot Transistors
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出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第12872号, 授与年月日:2024年9月20日, 学位の種別:課程博士, 審査員:真島 豊,神谷 利夫,鎌田 慶吾,片瀬 貴義,伊澤 誠一郎
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12872号, Conferred date:2024/9/20, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

THESIS OUTLINE

Study on Transport Properties of Single-Molecule and Single-Quantum-Dot Transistors

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Study on Transport Properties of Single-Molecule and Single-Quantum-Dot Transistors

Abstract

Transistors constitute the core of electronic circuits and drive the digital revolution. The physical limitation of conventional transistors based on drift transports motivates a growing interest in single-molecule transistors (SMTs) and single-quantum-dot transistors (SQDTs), as they are expected to realize ultrafast operation by utilizing resonant tunneling in which electrons across at a high speed of 1 attosecond (10^{-18} s). Here, I propose a promising platform for building SMTs and SQDTs based on heteroepitaxial spherical (HS)-Au/Pt nanogap electrodes. The transport properties via single π-conjugated molecules and single semiconductor quantum dots are studied at 9 K and room temperature. By modifying π-conjugated systems with different linkers, the transport properties of SMTs can be controlled.

1 Introduction

1.1 Background

Transistors constitute the core of electronic circuits and have been the fundamental building blocks of the digital revolution. With the miniaturization of transistors into the nanometer scale, nanoscale electronics has emerged as the successor to microelectronics, dominating electronics research for the past two decades. The semiconductor industry is committed to scaling down the silicon-based state-of-the-art CMOS transistors to sub-3 nm nodes in the near future. However, further enhancements in their characteristics and exploring new techniques are still necessary to reduce production costs while maintaining high-performance quality.

In this regard, single-molecule transistors (SMTs) and single-quantum-dot transistors (SQDTs) emerge as promising techniques to extend Moore’s Law beyond the limitations of nanometer-scale conventional FETs. They offer numerous advantages in device characteristics, including ultra-fast switching speeds, extremely low power consumption, size reduction to the molecular level, and facile fabrication with high yields. As a result, they are anticipated to become next-generation transistors at a sub-3-nm scale in the near future.

1.2 Objective of the Thesis

Toward the fabrication of next-generation sub-3 nm transistors, the establishment of SMTs and SQDTs emerges as promising techniques to extend Moore's Law beyond the limitations of conventional FETs and realize ultrafast operation through resonant tunneling transport. Objective of this thesis is to demonstrate transistor operation at the single-molecule and single-quantum-dot levels using HS-Au/Pt nanogap electrodes single π-conjugated molecules, and single semiconductor QDs.

Even though some pioneering studies about SMTs and SQDTs have been reported, they remain challenging in constructing functional electronic devices and realizing transistor applications promising for complementing and even replacing conventional MOSFETs. Taking advantages of HS-Au/Pt nanogap electrodes prepared by ELGP technique, these challenges are expected to be overcome.

To achieve the objective of this thesis, three sub-objectives are proposed:

(1) Demonstration of gate-modulated resonant tunneling transport with pronounced NDR effect on SMTs using HS-Au/Pt nanogap electrodes and π-conjugated quinoidal-fused oligosilole derivatives (Si2×2).

(2) Demonstration of resonant tunneling transport in chemically assembled SQDTs using HS-Au/Pt nanogap electrodes and colloidal CdS QDs.

2 Single-Molecule Transistors based on HS-Au/Pt Nanogap Electrodes

In this chapter, the resonant tunneling transports in two-terminal single-molecule junctions and three-terminal SMTs consisting of HS-Au/Pt nanogap electrodes and the Si2×2 derivatives (Si2×2_TphSH_phSH and Si2×2_TphCH$_2$SH_phCH$_2$SH) have been demonstrated. The former exhibited pronounced NDRs with a PV ratio of up to 30.1 without gate modulation due to the pinning effect via the chemisorbed phenyl thiol. Then, methylene groups are inserting to decouple the molecular orbitals from the electrode. The SMTs built by Si2×2_TphCH$_2$SH_phCH$_2$SH thereby exhibit effective gate modulations with a subthreshold swing of 100 mV/dec, suggesting the potential of Si2×2 derivatives for building SMTs by adjusting the interface coupling via linker modifications. The experimental transport properties of these two molecules are discussed and pronounced NDR effects are found with large PV ratios up to 147. The temperature dependence of NDR is confirmed between 9 K and 300 K, suggesting their application potential. By DFT calculation, these NDR effects can be attributed to the polarized HOMO under the electric field.

3 Single-Quantum-Dot Transistors based on HS-Au/Pt Nanogap Electrodes

In this chapter, CdS SQDTs based on C_8S-protected CdS QDs and HS-Au/Pt nanogap electrodes have been demonstrated. The transport properties demonstrated single-electron tunneling through the ground states of the QD, which can be observed up to room temperature. Theoretical fitting of the transport characteristics through the orthodox model evaluated the parameters in the SET circuit. The evaluated capacitance matched well with the calculated results, giving a large enough E_c to enable SET operation even at room temperature. The satellite lines originating from resonant tunneling through the discrete energy levels of the QD were observed in the stability diagram, which revealed the electronic structure under different charge states. The experimentally measured energy-level spacings in the QD agree with theoretical values. The increasing number of electrons in the QD tends to decrease the energy-level spacings between the ground states and the excited states. These results suggest that the SQDT fabricated by HS-Au/Pt nanogap electrodes is a robust platform for room-temperature SETs and can potentially explore new mechanisms in quantum physics.

4 Conclusions

In this thesis, I have fabricated SMTs and SQDTs using Si2×2 derivatives and colloidal CdS QDs, respectively. Their transport properties are investigated by electrical characterizations, temperature dependence tests, and theoretical calculations. The results in this thesis demonstrated a promising platform for building SMTs and SQDTs using HS-Au/Pt nanogap electrodes. The resonant tunneling transports through single Si2×2 molecules and single CdS QDs were discussed and thus demonstrated their potential applications of ultrafast transistor operation. The NDR effects and SET operations at room temperature reveal their potential for application as functional quantum devices.