SUMMARY OF Ph.D. DISSERTATION

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Title

Self-Organization and Single-Electron Operation of Group-IV Semiconductor Quantum Dot Structures

Abstract

Possibilities of adding new functions to conventional silicon (Si) semiconductor devices have been extensively explored utilizing quantum effects. Fabrication of high-quality quantum dots on Si substrates and identification of distinct physical effects in such structures hold a key for realization of new functionalities such as quantum information processing and single-electron signal processing. Motivated by these backgrounds, the present thesis describes investigation of self-organization phenomena of Ge-rich quantum dots formed on Si substrates and novel quantum phenomena observed in such nanostructures. Physics associated with Si single-electron devices are also exploited and an essential role of thermal fluctuation and stochastic effect are revealed in the single-electron ejection from a Si quantum dot.

Following the preface of Chapter I, Chapter II describes the growth process of Ge-rich quantum dots on Si surfaces via the Stranski-Krastanov mode. Ge atoms were deposited onto a Si substrate by molecular beam epitaxy. The resulting surface morphology as a function of the number of Ge atomic layers deposited was observed by the atomic force microscope. The effect of Si and Ge atomic diffusion was assessed statistically and the number of atoms required for formation of the critical nuclei was identified. In parallel, the internal composition and strain associated with the quantum dots were determined by Raman spectroscopy probing a specific Ge isotope as a marker. The transport phenomena of Si and Ge atoms among the quantum dots, wetting layer, and underlying substrate were quantitatively evaluated.

Chapter III describes the discovery of oscillatory behaviors of the photoluminescence intensity and energy recorded at temperature 2 K of Ge quantum dots embedded in a Si matrix. The oscillatory behaviors were found to arise from the phase modulation of the electron wave functions by the magnetic flux going through the quantum dots, i.e., due to the Aharonov-Bohm effect.

Chapter IV describes electron ejection behaviors in the Si-based single-electron ratchet transfer device. The ejection process of the first, second, and third electrons from the quantum dot was investigated around 16 K. The characteristic ejection time was found to depend on the number of electrons captured in the quantum dot and the thermal excitation across the barrier was found to be the major cause of the ejection. The accuracy of single-electron ejection was assessed and optimal operation conditions for controlled ejection of a desired number of electrons were found.

Chapter V describes how the single-electron ejection from the Si quantum dot depends on the periodic modulation of the potential barrier that confines the electrons. An enhancement of single-electron ejection was observed when the barrier-modulation period became comparable with the electron ejection time. This corresponded to the first observation of the stochastic resonance in a single-electron system showing that the temporally fluctuated ejection could synchronize with the externally applied modulation.

Finally, summary and future prospects are presented. A description of how the physical phenomena found and understood in the present thesis may contribute to the future development of silicon based nanostructure devices is given.