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Formation of Donor-induced Quantum Dots in Si Nano-channels Observed by Kelvin Probe Force Microscope

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学 位 論 文 要 旨

Abstract of Doctoral Thesis

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論文題目：ケルビンプローブフォース顕微鏡による Si ナノチャネル中のドナー誘起量子ドットの観察

Title of Thesis：Formation of Donor-induced Quantum Dots in Si Nano-channels Observed by Kelvin Probe Force Microscope

論文要旨：

Abstract：

Over the years the size of the field-effect transistor (FET) has been the main factor to be addressed when considering performance of silicon electronic devices. Nowadays, silicon technology is approaching the limits where further downscaling of conventional transistors is significantly hindered due to the discrete nature of dopants. To reach beyond the scaling limits, the concept of individual dopant-atoms used as building blocks of a device was introduced, underlying the new branch of electronic devices, namely dopant-atom transistors. In the basic variation of dopant-atom transistors, individual donors or cluster of donors placed within the FET channel works as a Quantum Dot (QD) allowing single electron tunneling transport.

In this work, formation of donor-induced QD in Si nano-channels doped by classical thermal diffusion with phosphorus (P) is addressed. The surface potential landscapes due to random P-donor distributions in FET channel are directly observed by Kelvin Probe Force Microscope (KPFM). As a new approach, comparative study is conducted by analysis of single-electron tunneling transport and surface potential measured by KPFM. The KPFM results are interpreted by correlation with surface potential simulation using Thomas-Fermi approximation.

At first, after the introductory part, experimental details are discussed. This includes silicon-on-insulator field-effect-transistor (SOI-FET) fabrication and explanation of experimental methods. Most importantly, it is emphasized that specific KPFM setup allows observation of FETs under operation. This allows investigation of FET channels depleted of screening electrons by negative back-gate biases. In the main part of the work the focus is placed on analysis and characterization of donor-induced QDs in different concentration regimes. In the experiment, two types of SOI-FET, representative for low-concentration regime (below metal-insulator transition, MIT) and high-concentration regime (above MIT) are

investigated by KPFM and electrical characterization.

In the first step of analysis, internal structure of donor-induced QD and the number of formed QDs in different doping regimes is addressed. The source-drain current vs. gate voltage (ID-VG) characteristics confirm single electron tunneling in low temperatures for both concentration regimes. The observed ID-VG features (together with Coulomb diamonds analysis) suggest that for low gate voltages transport is governed by only one dominant QD. This is further confirmed by the KPFM observation of depleted FET channels potentials, showing features due to individual donors (low-concentration regime) and donor clusters (high-concentration regime). The potential landscapes are dominated by single deepest potential well which is ascribed to dominant QD, regardless of doping concentration. The effect is suppressed for higher gate voltages. This result coincides also with simulation. Further analysis, by using Monte Carlo approach, show that statistically doping concentration affects primary the structure of dominant QD. At low concentrations, individual donors form most of QDs (i.e. "donor-atom" QDs). At high concentrations above metal-insulator transition, closely-placed donors form more complex QDs (i.e. "donor-cluster" QDs).

In the second step of analysis dispersion of dominant QD, its relation to macroscopic potential features, and influence on tunneling transport is discussed. The KPFM results correlated with simulation show that dominant QD position dispersion is related to macroscopic potential features arising from superimposed potentials of many donors. This macroscopic potential strongly depends on doping concentration and dimensions of doped area, when screening by electrons is low. In low-concentration regime the potential landscape is dominated by potential wells due to individual donors. In high-concentration regime the deepest-potential QD is formed at the bottom of macroscopic potential well. The correlation with ID-VG characteristics shows that at low gate voltages, tunneling appears sequentially via strongly dispersed donor-atom QDs (in low-concentration regime) or one localized donor-cluster QD (in high-concentration regime).

In summery, for the first time, an experimental correlation between single-electron tunneling characteristics and potential landscapes was used to investigate formation of donor-induced QD in different doping regimes. This study provides insights for designing optimized dopant-atom devices in which either single dopants or clusters of many dopants can be utilized as dominant QD.