論文の内容の要旨

論文題目　Site- and Shape-controlled Growth of Self-assembled InAs Quantum Dots and Their Device Applications
（自己組織化InAs量子ドットの位置・形状制御とデバイスへの応用）

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Self-assembled InAs quantum dots (QDs) have been attracting considerable attention owing to their unique properties, such as good optical properties, large orbital level splittings, and strong Coulomb correlation effects. Furthermore, InAs has a remarkable feature that it is not depleted even when directly touched by metals. These unique features make the InAs QDs attractive for future device applications for quantum information processing. Such device structures often require a single QD at prescribed positions. For example, when a QD is placed in photonic microcavities, it is possible to extract single photons or enhance interaction between excitons and cavity photons. Recently, it has also been reported that the self-assembled InAs QDs probed by metal nanogap electrodes (single QD transistors) exhibit single electron tunneling and clear shell filling. Furthermore, when the tunnel coupling between the metallic electrodes and the QD is strong, the single QD transistors exhibit strong spin-correlated transport, namely, the Kondo effect. In addition, when ferromagnetic or superconducting metals were used for the source and drain electrodes, very intriguing transport properties have been observed.

However, as is easily imagined, it is not an easy task to electrically access to single QDs since ordinary self-assembled InAs QDs are distributed randomly on GaAs surfaces. A typical device fabrication process is stochastic and the fabrication yield is usually very low (typically, ≤ 1 %), leaving the device applications still at a preliminary stage. Therefore, the site-control of QDs is very crucial.

In this work, we have fabricated position- and size-controlled InAs QDs by using atomic force microscope (AFM)-assisted anodic oxidation and investigated how the size of the QDs depends on the AFM-oxidation condition. Optical and transport properties of the site-controlled QDs also have been studied. We could clearly see emission even from single layer QD arrays and narrow emission peaks from the ground states as well as higher sublevels in the QDs were clearly resolved, indicating that good crystalline quality. Finally, we fabricated lateral single QD junction structures by depositing Au/Ti nanogap electrodes directly on the QDs. 80% of the fabricated nanojunctions contained single QDs, the fabrication yield of which was dramatically improved from that for the case without site-control (a few %). We observed clear diamond-like patterns in the Coulomb stability diagram, indicating that the fabricated single QD transistors operate as single electron transistors.

This thesis is organized as follows. In Chapter 1, we first have reviewed basic concepts of QDs and selective growth of self-assembled InAs QDs performed so far. We state the purpose for this work.

In Chapter 2, we describe experimental technique of the AFM-assisted anodic oxidation for site-controlled InAs QDs used in this work. First, basic concepts of AFM-assisted anodic oxidation will be briefly described. Second, we will investigate the thermal stability and chemical composition of GaAs-oxides grown by AFM-assisted anodic oxidation to identify the condition suitable for fabricating oxide nanomasks for molecular beam epitaxy (MBE). The oxides grown at bias voltages, V_{ox}, less than 30 V were desorbed after standard thermal cleaning in MBE, while the oxide patterns fabricated at $V_{ox} \geq 40$ V survived on the GaAs surfaces. From X-ray photoemission spectroscopy, we have found that the better thermal stability of AFM-oxides grown at $V_{ox} > 40$ V can be attributed to the formation of Ga_2O_3 and that Ga_2O_3 can be used as nanomasks for site-controlled MBE growth.

In Chapter 3, we will describe optimal growth condition for position- and size-controlled InAs QDs by using AFM-assisted anodic oxidation and investigated how the size of the QDs depends on the AFM-oxidation condition. It was found that the nucleation of the QDs is strongly affected by the growth temperature and nanohole size. It was also found that the site-controlled InAs QDs have clear facets, suggesting their excellent crystalline quality. Nucleation of undesired dots was effectively suppressed. The size-control of InAs QDs was also carried out by changing the V_{ox} and found that the lateral size of the QDs can be reproducibly controlled over a range of 30-180 nm simply by tuning V_{ox}. We have further investigated the growth of double QDs by changing the separation, d, of two oxide dots. When d = 40 nm, we obtained elongated single QDs. However, when $d \geq 80$ nm, double QDs were obtained. Furthermore, the coupling between the two QDs was continuously changed when d was varied from 80 nm to 140 nm.

In Chapter 4, we will describe the morphologies and optical properties of the site-controlled InAs QDs by AFM-assisted oxidation. It is found that the morphology of the site-controlled QDs strongly depends on the growth temperature, T_g, and that the uniformity is dramatically improved when QDs are grown at T_g = 520 °C, which is higher than the commonly used temperatures (480-500 °C). Although no photoluminescence (PL) was observed from QDs grown at 480 °C, we could clearly see emission even from single layer QD arrays grown at 520 °C. Narrow emission peaks from the ground states as well as higher sublevels in the QDs were clearly resolved, indicating that good crystalline quality and size-uniformity were achieved at T_g = 520 °C. Furthermore, it was found that the size of the site-controlled QDs is almost unchanged upon the variation in the InAs supply during QD formation and that excessive In is used mainly for growing unintentional self-assembled QDs.

In Chapter 5, we will describe the transport properties of site-controlled InAs QDs as their device applications. We fabricated lateral single QD junction structures by depositing Au/Ti nanogap electrodes directly on the QDs. 80% of the fabricated nanojunctions contained single QDs. The fabrication yield of single QD junctions was dramatically improved from that for the case without site-control (a few %). We observed clear diamond-like patterns in the Coulomb stability diagram measured at 4.2K, indicating that the fabricated single QD transistors operate as single electron transistors.

Finally, Chapter 6 will summarize this thesis.