論 文 の 内 容 の 要 旨

論文題目 Growth of InAs/GaAs Quantum Dots-in-Nanowire on Si and Its Application to Single Photon Emitter
(InAs/GaAs量子ドットナノワイヤのシリコン基板上成長と単一光子発生素子への応用)

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A quantum dot is a nano-sized semiconductor structure in which carriers are confined in three dimensions. The electron behavior is fully quantized by quantum dots confined to a ten-nanometer scale. This effect creates δ-functional discretized states in the semiconductor. This property is useful for many applications such as telecommunication devices (lasers, non-linear optical devices, optical amplifiers), quantum information technology and quantum cryptography.

Nanowire structures have been attractive for applications in photonics and quantum information technology due to their small diameters of less than a few hundred nm and height of several μm. To date, many reports have been made on nanowire growth using homo- and hetero-epitaxial growth systems, for example, GaAs nanowires on GaAs substrate, GaAs nanowires on silicon substrate, InAs nanowires on Si substrate, and so on.

By combining quantum dots and nanowires, it is possible to form an efficient single photon emitter directly on silicon substrate.

In this thesis, I will present my research about quantum dots embedded in a nanowire structure grown on a silicon substrate for single photon emitter applications. For this purpose, I realized the growth of GaAs nanowires on silicon, and also the growth of InAs quantum dots on the GaAs nanowire. Optical measurements of the InAs quantum dots were also performed. All of the samples were grown by molecular beam epitaxy method for high crystal quality with high controllability.

GaAs nanowires were grown by the self-catalytic growth method, which does not use external catalyst materials. A silicon (111) substrate with silicon native oxide was used for this work. The silicon oxide layer has pinhole structures with dimensions of of a few angstroms. These holes act as a growth window for nanowire structures. Grown nanowires are perpendicular to the Si(111) substrate, and they have {1-10}-facet sidewalls. I investigated the growth parameters which affect the shape and density of the GaAs nanowires. The growth mechanism of the GaAs nanowire (Vapor-Liquid-Solid (VLS) and non-VLS growth) could then be clarified. I successfully grew non-VLS GaAs nanowires under low As flux conditions, using a Ga pre-deposition method. The transition between VLS mode growth and non-VLS mode growth occurs when the As flux changes from 1.5×10^{-5} Torr to 6.0×10^{-6} Torr, using Ga pre-deposition method under constant Ga flux. I attribute this to the As rich environment at the growth site surface which occurs under Ga pre-deposition. I have also suppressed the spontaneous growth of undesirable surface nanostructures on the Si substrate by eliminating the As flux and supplying Ga flux before the nanowire growth. For this reason, the background luminescence from surface nanostructures can be reduced, simplifying the optical measurements of anti-bunching phenomenon in InGaAs/GaAs quantum dot embedded in nanowires directly grown on silicon. The method I have developed enables us to characterize single GaAs nanowires with hetero-structure on a silicon substrate without any post-processing. This method can potentially be used to realize highly efficient quantum dot embedded in nanowire based quantum information devices grown on a silicon substrate.

Next, InAs quantum dots were grown on the GaAs nanowires described in the previous paragraph. In and As were supplied to GaAs nanowires. Two types of quantum dots were observed. On smaller nanowires with diameters less than 100 nm–, monolayer fluctuation quantum dots were formed. In contrast, on-bigger nanowires with diameters more than 100 nm-, quantum dots grown under the Stranski-Krastanov growth mode were formed.

The single photon emission properties of the quantum dots embedded in nanowire structures were measured by photoluminescence experiments at cryogenic temperature. Successful growth of InAs quantum dots embedded in GaAs nanowire structures on silicon substrates with an AlGaAs shell structure was verified. Sharp emission peaks from the structures were observed using micro-PL spectroscopy. The narrowest linewidth of 162 μeV was observed, which demonstrates high optical quality of the quantum dot-in-nanowire. The generation of single photons from the structures has also been clearly demonstrated ($g_{(2)}(0)=0.18$).-. It is likely that the good optical qualities originate from the high crystal quality of the quantum dot structure, which was formed by S-K growth mode.

Our foreign-catalyst-free growth method will open the way toward facile integration of such emitters into future ‘on-silicon’ quantum optical circuits. The growth technique described here could be used not only for single photon emitter growth, but also for understanding the formation of self-catalytic grown nanowire structures.