Formation and optical properties of low density and area-controlled InAs quantum dots

低密度位置制御 InAs 量子ドットの形成とその光学特性

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CHAPTER ONE

INTRODUCTION

1.1 Background

Single photon emitters which deliver a train of pulses that contain only a single photon are essential for quantum cryptography and quantum information processing. [1][2] The fundamental impossibility of duplicating the complete quantum state of a single particle prevents any potential eavesdropper from intercepting the message without the receiver's noticing. Compared with Poisson-distributed sources, single photon emitters produce a single photon at a time, similarly to a dropper as shown in Fig.1-1.

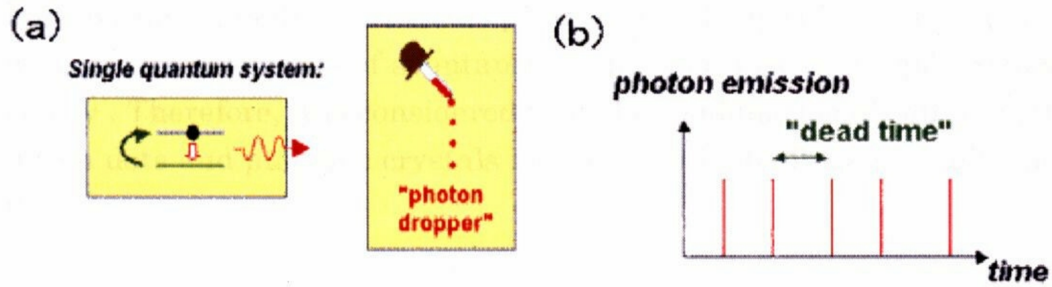

Fig.1-1 (a) Single quantum emitters produce a single photon at a time, similarly to a dropper. (b) Antibunched photon sequence from a single quantum emitter.

This so-called 'antibunching' of emitted photons were first demonstrated in the fluorescence of a very faint atomic beam excited by a continuous laser (Kimble *et al* 1977 [3]). Since the atomic beam was faint, at most one atom was in the laser beam at a given time, and most of the time the laser focus was empty. Fluorescence therefore arose from single atoms. In contrast to the Poisson distribution in an attenuated laser beam, where two photons could be separated by any delay, very short delays were not allowed for photons emitted by a single atom. The photons have a tendency to be emitted one by one, i.e. they were 'antibunched'.

Since then, single photon emissions have been demonstrated using a variety of devices, including single atoms [3-5], single molecules [6][7], color centers[8][9] and quantum dots[10-46] because antibunched photons have been observed in such confined single nanometer-size objects which are called single quantum systems.

Among them, self-assembled quantum dots has been of great interest as single photon sources because they are relatively stable, have narrow spectral linewidths and rapid radiative decay rates, and can be integrated into larger fabricated structures as microcavities. In microcavities, collection efficiency of photons is improved due to the spatial limitations and the radiative lifetime of emitters is also significantly shortened due to the Purcell effect. This improves device performance and makes single photons indistinguishable. Indistinguishable single photons can also be applied to quantum information processing.

Photonic crystal microcavities, which are the periodic dielectrics of different refractive indices, have attracted much attention due to the prospect of controlling a spontaneous emission.[11-13] They tightly confine photons within a small V due to the photonic band gap (PBG) effect and thus offer large enhancements of spontaneous emission rate and light extraction efficiency . Therefore, it is considered that the combination of self-assembled quantum dots and photonic crystals may lead to high efficient single photon emitters.

1.2 Motivation

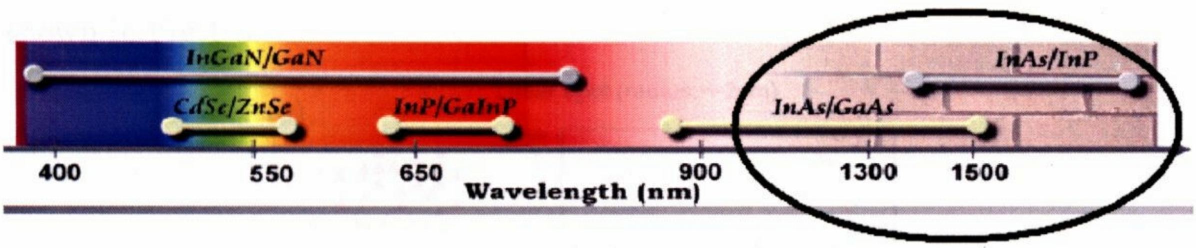

Fig.1-2 Emission wavelengths of self-assembled quantum dots for different material systems

As introduced in section 1.1, self-assembled quantum dots are receiving considerable attention as single photon emitters because single quantum dots obtained by strain-driven nucleation in the Stranski–Krastanov growth mode have been shown to emit single photons, and thus represent a promising candidate for a solid-state, electrically pumped single-photon source. However, most studies so far have concentrated on the $\lambda < 1000$ nm wavelength range, while fiber-based quantum cryptography requires emission wavelengths matching the 1300 or 1550 nm transmission windows of optical fibers.

InAs/InP quantum dots and InAs/GaAs quantum dots have been exhibited a great deal of attention because they emit at telecommunication bands (1.3μm and 1.5μm) which are suitable for optical fiber transmission as shown in Fig.1-2. For InAs/InP quantum dots, single photon pulses at 1.3μm and 1.5μm were achieved for the first time by the group of Prof. Y. Arakawa/Fujitsu group. [14] However, InAs/InP quantum dots are very sensitive to the temperature due to their small band-offset. Due to the larger band-offset of the InAs/GaAs QDs, and the lower cost of GaAs substrate, associated with its compatibility with other semiconductor technologies, the InAs/GaAs QDs have been the subject of intensive research for single photon emitters. The motivation of this study is to fabricate the suitable InAs/GaAs quantum dots for high efficient single photon emitters. We think that there are three main issues in order to establish this aim.

The first issue is the density of quantum dots. For conventional laser diodes, namely edge emitting lasers and vertical cavity surface emitting lasers, high density quantum dots are desirable for maximizing the ground state material gain. In contrast, quantum dots of much lower density are required to isolate a single quantum dot system for single photon emission as shown in Fig.1-3.

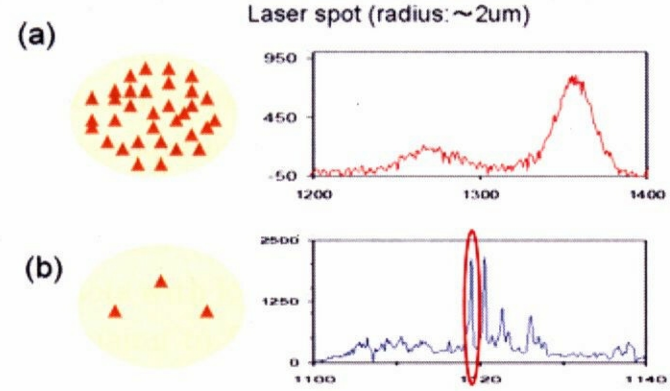

Fig.1-3 PL luminescence from (a) high density quantum dots (b) low density quantum dots

In order to achieve this purpose, low density quantum dots ($< 10^7 cm^{-2}$) are needed because in such low density, only a few quantum dots are pumped by a laser spot, and thus we can eject single photons from single quantum dots.

The next issue is the emission wavelengths of quantum dots. As mentioned above, fiber-based quantum cryptography requires emission wavelengths matching the 1300 or 1550 nm transmission windows of optical fibers because they have the lowest optical loss in all optical fiber bands as shown in Fig.1-4. For long distance transmission, quantum dots which emit at wavelengths of 1.3um or 1.55um are crucial.

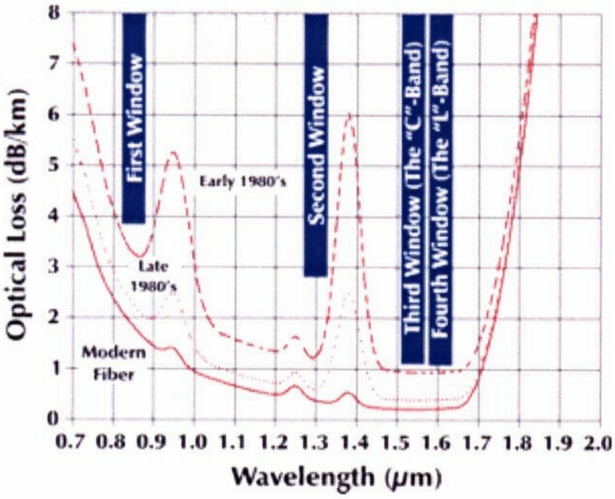

Fig.1-4 Optical loss dependence on emission wavelength

The last issue is the area control of quantum dots. The Stranski-Krastanow (SK) growth mode is the most widely used approach for the fabrication of quantum dots, but it results in random positioning of the quantum dots. For combination with photonic crystals, a technique to control the location of quantum dot growth is required to avoid optical absorption and attain high reflectivity.

Considering these issues, it would be advantageous to achieve the InAs/GaAs quantum dots with low densities, long emission wavelengths, and it would be also promising to fabricate the area-controlled InAs quantum dots.

1.3 Overview of this thesis

In this thesis, the formation and optical properties of low density InAs quantum dots and area-controlled InAs quantum dots is closely investigated for high efficient single photon emitters. In chapter.2, formation and optical properties of InAs quantum dots with low densities and long emission wavelengths are investigated. In chapter.3, fabrication of patterned SiO_2/GaAs substrates for selective growth is introduced. In chapter.4, preliminary studies of growth conditions for area-controlled quantum dots were described. In chapter.5, formation and optical properties of area-controlled quantum dots are studied.