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Molecular beam epitaxy grown indium self-assembled plasmonic nanostructures

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ABSTRACT

We describe molecular beam epitaxy (MBE) growth conditions for self-assembled indium nanostructures, or islands, which allow for the tuning of the density and size of the indium nanostructures. How the plasmonic resonance of indium nanostructures is affected by the island density, size, distribution in sizes, and indium purity of the nanostructures is explored. These self-assembled nanostructures provide a platform for integration of resonant and non-resonant plasmonic structures within a few nm of quantum wells (QWs) or quantum dots (QDs) in a single process. A 4× increase in peak photoluminescence intensity is demonstrated for near-surface QDs resonantly coupled to indium nanostructures.

1. Introduction

The field of plasmonic nanostructures, where small volume structures can enhance electromagnetic fields that can be coupled to semiconductor quantum confined gain medium, is an expanding area of research. It has been shown that MBE grown silver films have improved optical constants, i.e. closer to intrinsic values, over e-beam or physical vapor deposited silver films [1]. This gives a possibility for improvements in the quality of plasmonic nanostructures or nano-antennas. It has also been shown that MBE can be used to grow site-controlled structures out of silver [2] and self-assembled structures with silver [3] and indium [4]. MBE growth allows for higher quality metallic nanostructures due to the improved optical constants and the self-assembly creates a clean interface between the metallic nanostructure and semiconductor underneath. In the self-assembled case there is also no need for fabrication or post-processing for optical experiments, eliminating possible sources of impurities and contamination. By tuning the sizes of these nanostructures the resonant wavelength can be tuned [5] to be in resonance with QWs [6,7] or QDs [8] just a few nanometers beneath the metallic structures. Growing these resonant indium islands in the same process as the semiconductor growth with MBE now opens up the possibility of encapsulating [9] the islands with more semiconductor material, including gain material. This would allow for larger coupling effects and possibly compensating metamaterial losses.

Here we present MBE growth conditions for indium islands, which allow for the tuning of the density, to well below 1 μm^{-2}, and size, from ~100 nm up to ~1.5 μm, of the indium islands. The larger island diameters are a result of a slow indium growth in the 1 ML/hr range, allowing for migration of the indium atoms throughout the growth.

2. Materials and methods

All samples have been grown on (100) GaAs wafers. The indium island samples have been grown in two different machines. The first is a Riber 32P where the sources are mounted on the rear vertical wall of the MBE growth chamber and aimed at the substrate which is mounted 25° from vertical, and 13° away from the most uniform growth position. In this chamber we have utilized 500 μm thick, double-side polished, two inch wafers cleaved into quarters for sample growth. These quarter wafers are held in three inch molybdenum substrate mounts (molyblocks) for quarter wafers with two tabs along the perpendicular sides. The other chamber used is a Riber 412 where the sources are mounted on the bottom of the MBE growth chamber and aimed at the substrate which is mounted horizontally in a five inch platen and the substrate is centered in the platen. In this chamber the growth is done on

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350 μm thick, single-side polished, full two inch wafers which are n-doped with silicon (10^{-18} cm^{-3}). This chamber was used for all samples discussed below that have been grown with doped semiconductor layers. Both chambers utilize effusion cells with 7 N (7N5) purity indium in the Riber 32P (Riber 412).

After de-oxidizing the substrate, >400 nm of GaAs is grown at a substrate temperature of ~ 580 °C. For samples grown with InGaAs QWs or InAs QDs the substrate temperature is dropped to ~ 485 °C for the growth of these structures. The QW or QDs are then capped with between 3 and 10 nm of GaAs grown at the same substrate temperature. For the indium island growth the substrate temperature is lowered by cutting off the current to the substrate heater. At a substrate temperature of ~ 300 °C the arsenic flux is cut off. Once the arsenic flux is off, the substrate heater is set at a constant current and the substrate is allowed to come to an equilibrium temperature, ~ 130 °C as measured with a type C thermocouple, while arsenic continues to be pumped out of the chamber. This time has been varied between 1 and 12 h. The indium island deposition then takes place with growth rates (beam equivalent pressure) between 0.27 ML/s (3.02×10^{-7} Torr) and 1 ML/hr or 0.00028 ML/s (3.97×10^{-10} Torr). In the latter case the indium cell temperature is only 60 °C above the standby temperature of the cell. The indium growth rate is given as the growth rate of InAs as calibrated from InAs QD growths.

Samples are characterized using atomic force microscopy (AFM), scanning electron microscopy (SEM), tunneling electron microscopy (TEM), energy dispersive x-ray spectroscopy (EDS), Fourier transform infrared (FTIR) transmission measurements, and photoluminescence (PL). By utilizing standard image processing techniques the sizes of the islands are extracted from AFM and SEM images.

3. Results

An interesting aspect of the indium island sample growths is the different distribution in island sizes achieved by the two different machines used. While there is expected to be small variations in substrate temperature and flux uniformity it is not expected that the indium islands grown in one chamber would have a Gaussian-like distribution in size while the other chamber would produce size distributions with a clear tail on the short side of the distribution. This is seen in Fig. 1(a) and (b) for the diameter

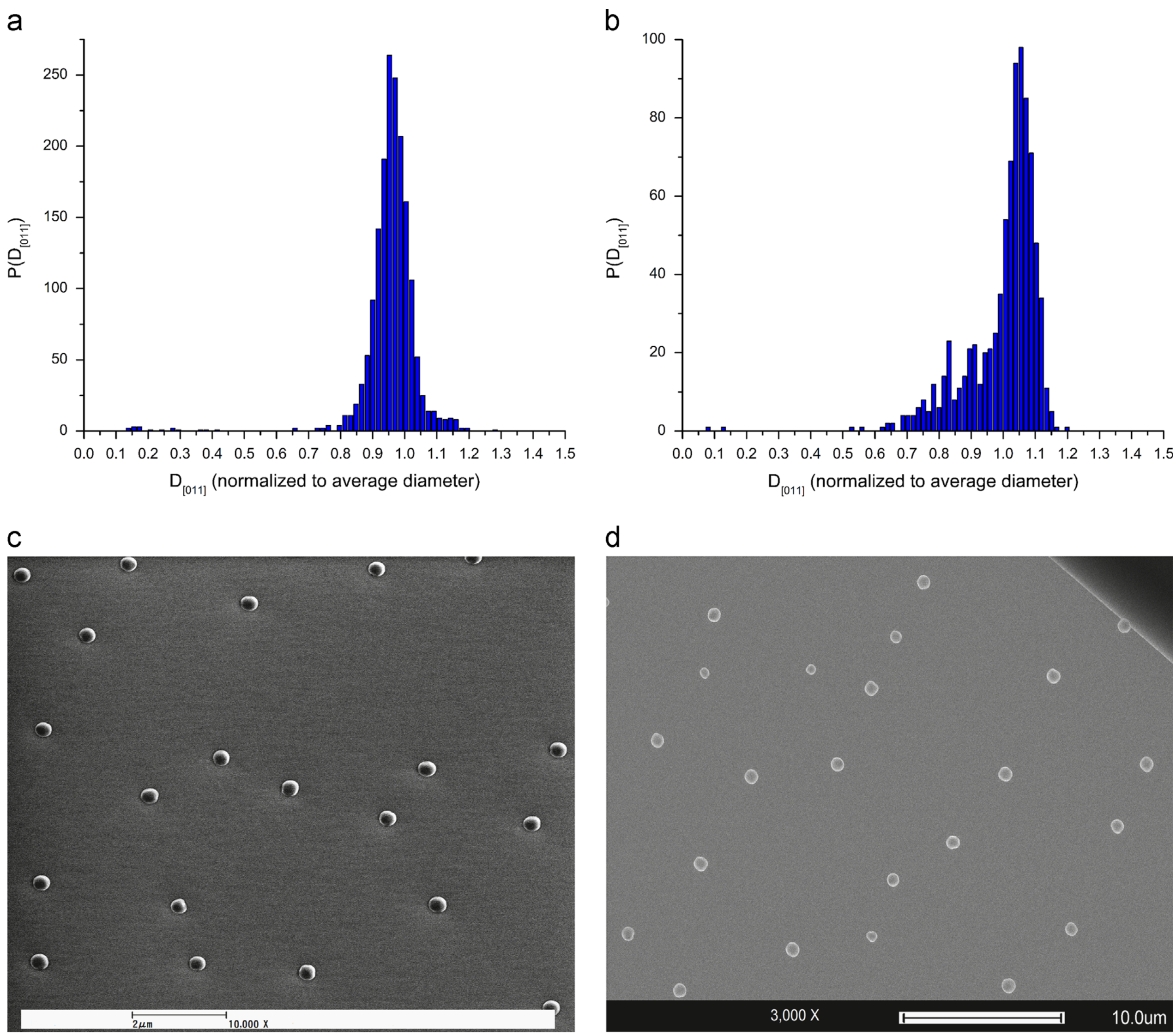

Fig. 1. Distribution of the diameter of the indium islands along the (011) crystal axis for a sample grown in the Riber 32 (a) and a sample grown in the Riber 412 (b). The distributions are scaled to their average diameter, which are 385 nm with a standard deviation of 34 nm and 834 nm with a standard deviation of 94 nm for samples shown in (a) and (b), respectively. (c) and (d) SEM images corresponding to the distributions in (a) and (b), respectively.

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