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In situ Metal Mask for Selective Area Growth of Thin Epitaxial Layers

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1. Introduction

Self-assembled quantum dots (QDs) are promising in terms of their applications in high-performance optoelectronic devices including laser diodes and high-speed optical switches [1,2]. We have recently proposed and demonstrated an ultra-small and ultra-fast photonic-crystal-based symmetrical-Mach-Zehnder-type all-optical switch (PC-SMZ) [3] and a flip-flop (PC-FF) device [4] in which QDs are used as an optical nonlinear material. These devices require a large number of highly uniform, high-density QDs in the PC straight waveguide regions selectively. For this purpose, we have developed an *in situ* metal mask that enables the selective formation of molecular beam epitaxially (MBE) grown QDs in narrow regions [5]. In order to achieve high performance operation of the PC-SMZ and PC-FF, the step height of the selective area growth (SAG) region should be suppressed as much as possible in addition to the abovementioned requirements since the steps at the interfaces cause the reflection of the propagating light and band narrowing of the PC waveguides. On the other hand, if the selectively grown layer is very thin, it cannot be viewed using an optical microscope and/or a scanning electron microscope. To resolve these problems, we have developed a new *in situ* mask that enables the formation of marker layers for ensuring alignment in the processes following the selective growth. The effectiveness of the mask was demonstrated by the fabrication of PC-SMZ device structures on the selectively grown QD regions.

2. Developed *in situ* Metal Mask

Figure 1 shows a schematic illustration of the fundamental principles of epitaxial growth using the *in situ* mask. A mechanical mask with window-type openings is held between the evaporating sources and substrate during MBE growth. This mask can be fitted and removed in an ultra-high-vacuum (UHV) environment. The molecular beams of constituent materials such as In, Ga, and As atoms can be irradiated onto the sample surface through the window openings in the mask. The edges of the windows are beveled to an angle of 40° in order to prevent shadowing from the incident molecular beams during growth. The reverse side of the center region of the metal mask, where selective growth is performed, is ground to a depth of 100 μm in order to maintain a constant distance between the metal mask and substrate surface. Setting the mask on the sample holder during growth permits selective growth only in the open regions.

Figure 2 shows a schematic diagram of a developed metal mask and the principle of fabricating additional marker layers for ensuring alignment in the processes following the selective growth. We fabricated another small windows and a shutter mechanism on the mask holder, as shown in Fig. 2. The additional windows are fabricated outside the selectively grown regions for devices. The shutter can be opened and closed by rotating the sample holder due to the weight of the shutter itself. In order to ensure this shutter movement, a weight is attached to the end of the shutter. The shutter is opened during selective growth as shown in Fig. 2(a). After selective growth, the temperature of the sample is lowered to prevent the desorption of V-group element atoms on the sample surface due to the interruption of the irradiation of the flux by the shutter. The sample holder is rotated by 180° using an MBE manipulator, as shown in Fig. 2(b), such that the shutter is closed and the marker layers can be grown only in the additional small open areas.

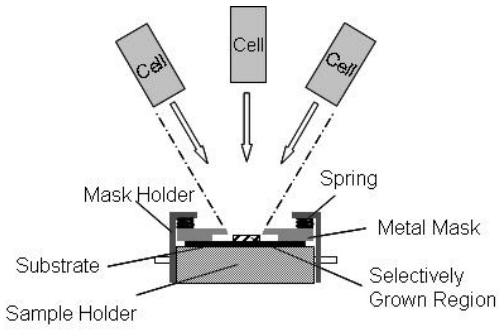

Fig. 1 Schematic diagram of the epitaxial growth procedures using the *in situ* metal mask.

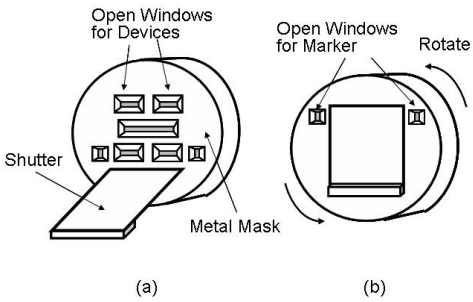

Fig. 2 Schematic diagram of the principle of fabricating a marker layer using the proposed metal mask.

The material chosen for fabricating the marker layer generally depends on the growth systems. In this study, a GaAs layer grown at a low temperature was used as a marker layer.

3. Fabrication of PC-SMZ Structures on the Selectively Grown QD Layers

To explore the effectiveness of the developed *in situ* mask, we used it to selectively grow QD structures in narrow regions and fabricated PC-SMZ device structures on the sample. Figure 3 shows an optical microscope photograph image of the fabricated sample. We have thus successfully aligned the PC-SMZ structures with straight waveguide regions using the fabricated marker layers. This result indicates that the marker layer fabrication system is a powerful function for ensuring the alignment in the subsequent processes, especially in cases where the selectively grown layer cannot be recognized by other methods, e. g., by using an optical microscope.

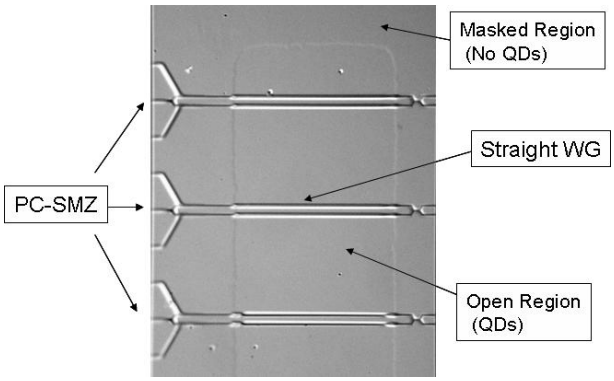

Fig. 3 Optical microscope image of PC-SMZ devices that were fabricated on selectively grown QD regions using the *in situ* metal mask. For this sample, a rather thick selectively grown layer for devices was used in order to recognize the SAG regions using an optical microscope.

4. Summary

We have developed an *in situ* mask that enables the selective formation of thin layers in narrow regions. This mask can be fitted to a sample holder and removed in a UHV environment; therefore, device structures can be fabricated without exposing the sample surfaces to air. Moreover, this mask enables the formation of marker layers for ensuring the alignment in the processes following the selective growth. The developed method is applicable not only to our proposed PC-SMZ and PC-FF devices but also to future high-performance functional devices such as multi-wavelength light-emitting source devices and PC microcavities [6]. The *in situ* mask method provides additional latitude in designing optoelectronic and electronic devices.

Acknowledgement

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