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Formation of InGaAs/InAlAs Quantum Wires and Dots with Extremely Smooth Facets on Mesa-Patterned (001)InP Substrates by Selective Molecular Beam Epitaxy

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A systematic growth experiments were undertaken for successful growth of InGaAs/InAlAs quantum wires and dots on patterned InP substrates by selective molecular beam epitaxy. Multi-layer test structures consisting of InGaAs and InAlAs alternate layers were formed on 7 different mesa patterns having stripe- and square-shaped mesa oriented along <110>,<$\bar{1}$10> and <100> directions. Growth on stripe-mesas along <$\bar{1}$10> and <100> directions, and growth on square-mesas with (201) sidewall facets resulted in very smooth facets, cross-sectional and lateral uniformity of the structure, and good growth selectivity. By using these patterns and optimized growth conditions, InGaAs quantum wires and dots were successfully formed.

1. Introduction

In view of applications to next-generation electronic and optoelectronic devices, various approaches for nanostructure formation are being intensively studied. Among them, selective molecular beam epitaxy (MBE) growth on mesa-patterned substrates appears to be particularly promising due to capability of size reduction without process-induced damage and to formation of uniform nanostructures with smooth facets. As compared with MBE growth using patterned SiO_2 or Si_3N_4 masks,[1] which usually requires irradiation by atomic hydrogen for successful growth, this approach is much simpler and more versatile and can be done using a standard MBE system. It has so far been applied mostly to the AlGaAs/GaAs system.[2]

The purpose of this paper is to systematically clarify the growth conditions for successful formation of InP-based InGaAs/InAlAs quantum wires and dots by selective MBE growth on mesa-patterned (001) InP substrates. This material system is attractive for realizing high temperature operating quantum devices due to its large conduction band discontinuity and superb electron transport. Various stripe- and square-mesa patterns were prepared along various crystal orientations and MBE growth were made. The growth led to formation of sidewalls consisting of a variety of facets. Smoothness of sidewalls depended strongly on initial patterns and growth conditions. Based on the criterions concerning uniformity and growth selectivity, wire formation on stripe mesa along <$\bar{1}$10> and <100> directions and dot formation on pedestals with (201) sidewall facets are shown to be appropriate. Using optimized selective growth conditions, InGaAs quantum wires and dots having smooth sidewall facets were successfully fabricated.

	starting pattern		growth result			
	direction	cross-section	cross-section	uniformity: cross-section	uniformity: lateral	growth selectivity
A	<110>	SBW (110)	(111)B	×	×	○
B	<110>	HBr (111)B	(311)B (111)B	○	×	×
C	<$\bar{1}$10>	SBW (111)A	(311)A	○	○	○
D	<100>	SBW (100)	(110)	○	○	○

Table1 Summary of growth on stripe mesa.

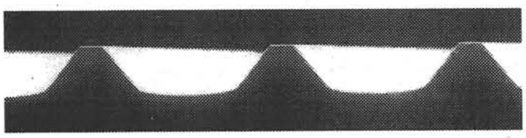
	starting pattern	growth result: plan-view	cross-section <110>	cross-section <$\bar{1}$10>	uniformity: plan-view	uniformity: cross-section	growth selectivity
E	SBW 2 μm <100>	(101) (113)B (421)	(113)B (421)	(111)A (421)	×	×	○
F	SBW 2 μm <110>	(421) (101) (113)B (111)B (111)A	(421)	(113)B (421)	×	×	○
G	HBr 1 μm (201) <100>	(101) (421)	(110) (421)	(421)	○	○	○

Table2 Summary of growth on square mesa.

2. Preparation of Patterned Substrates

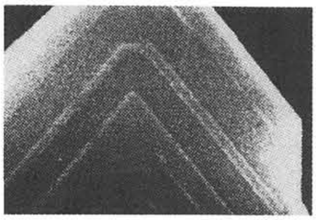
7 different patterned substrates were prepared for growth experiment. They included 4 types of stripe-mesa patterns(A-D) for wire formation and 3 types of square-mesa patterns(E-G) for dot formation. The structures of starting patterns are summarized in the left-most columns of Tables 1 and 2 for wire and dot formation, respectively. They were prepared using the standard photolithography and subsequent wet chemical etching either in a saturated Br-water (SBW) solution or in an HBr solution as indicated in Tables 1 and 2. The width of the stripe mesa and the side dimension of the square mesa were 1-2 μ m with the etching depth of 0.4-1.0 μ m. The sidewalls of patterns B, C and G became well-defined (111)B, (111)A and (201) facets,

(a) pattern A

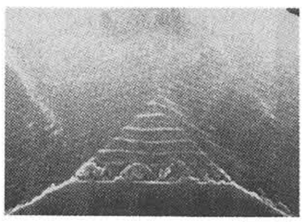


(b) pattern C 3μm

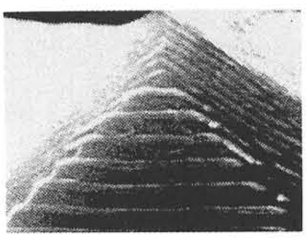
Fig.1 Examples of SEM micrographs of starting stripe mesa patterns.



(a) pattern A 200nm



(b) pattern C 200nm



(c) pattern D 200nm

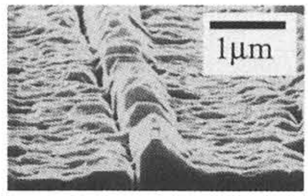
Fig.2 Cross-sectional SEM micrographs of the InGaAs(10 nm)/InAlAs(50nm) structures grown on stripe mesa.

respectively. On the other hand, the sidewalls of patterns A, D, E and F were perpendicular to the (001) mesa terraces. Some examples of cross-sectional SEM micrographs of the starting patterns are shown in Fig. 1. As seen in Fig.1, uniformity of the starting patterns were quite good.

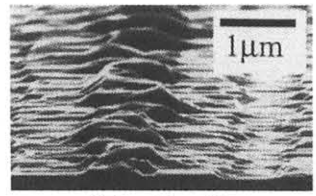
3. MBE Growth and Properties of Grown Structures

3.1 MBE Growth Condition

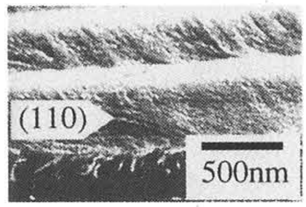
Wire and dot 'test structures' consisting of multiple alternate layers of InAlAs and InGaAs were grown on the patterned substrates using a standard MBE system. Two different thickness configurations were used for test structures. Namely, beam flux ratio and growth time were chosen such that they produced superlattices consisting of either InGaAs(10 nm)/InAlAs(50 nm) or InGaAs(50 nm)/InAlAs(10 nm) on the planar InP substrates placed right next to the patterned substrates. The growth rates for InGaAs and InAlAs on the planar substrates were both set at 600 nm/h, and a growth temperature of Tg=500-580℃ were used. The As_4 pressure was varied in a range from 0.5



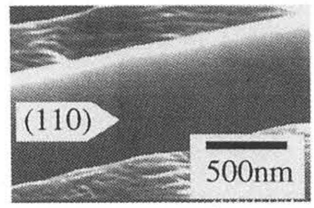
(a) pattern A
T_g=500℃



(b) pattern B
T_g=500℃



(c) T_g=500℃



(d) T_g=580℃

pattern D

Fig.3 Plan-view SEM micrographs of theInGaAs(10nm)/InAlAs(50nm) structures grown on stripe mesa.

to 3.0×10^{-6} Torr. In this range, As stabilized surfaces were maintained during the growth.

3.2 Results on Wire Growth

The grown structures were characterized by SEM observation and evaluated in terms of the structural uniformity and the growth selectivity. The growth result on wire formation is summarized in Table 1. As examples of cross-sectional structures obtained after growth, cross-sectional SEM image of InAlAs test structures grown at 500℃ on pattern A, C and D are shown in Figs.2(a),(b) and (c), respectively. In all cases, the reduction of terrace width and increase of growth rates on the terraces took place as the growth proceeded, and these accompanied formation of new characteristic sidewall facets just next to the terraces. Thus, the sidewalls of the test structures grown on the pattern A became (111)B facets. On the other hand, (311)B, (311)A and (110) facets appeared for the growth on the patterns B, C and D, respectively.[3]

Uniformity of the cross-sectional structures was very good in the growth on the patterns B, C, and D. However, uniformity of the cross-section was rather poor in the case of growth on the pattern A.

As examples of plan-view structures obtained after growth, Figures 3(a) and (b) show plan -view SEM images of InAlAs test structures grown at 500℃ on patterns A and B, respectively, and Figs.3(c) and (d) show those grown on pattern D at 500℃ and 580℃, respectively.

As seen in Figs.3(a) and (b), patterns A and B gave extremely poor uniformity along the wire direction. On the other hand, as shown in Fig.3(c) and (d), well-defined ridge structures surrounded by (110) facets were formed on patterns D having the mesa stripes along <100> direction. Particularly, as seen in Fig.3(d), uniform ridge structure with extremely smooth (110) sidewall facets were formed in the case of the growth on pattern D above 550℃. The growth on pattern C also resulted in a uniform ridge structure with smooth (311) facets.[3] On the other hand,

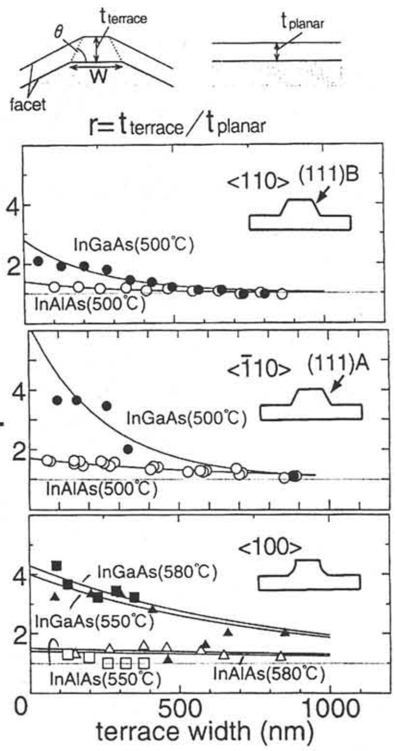


Fig.4 The selectivity of growth on stripe mesa

attempts to improve uniformity for pattern A and B by changing T_g did not succeed. This is different from the case of the AlGaAs/GaAs system where a uniform ridge quantum wire can be grown using this pattern.[4] The reason may be related to difference in the depth of missing dimer rows on (2x4) surfaces recently found by our group using UHV-STM.[5] Namely, in InP- related materials, missing dimers have a depth of 0.5 ML and produce In-covered migration channels in the <110> directions whereas that of the GaAs-related materials is 1 ML and no Ga-channels are formed.

Figure 4 plots the measured selectivity for wire growth in terms of the ratio, r, taken between the growth rate at the top of each pattern and that on the planar substrate. Since larger values of r facilitate formation of carrier confining structures on the terrace, patterns C and D having <$\bar{1}$10> and <100>-oriented mesa stripes are suitable for formation of quantum wires.

According to the growth results summarized in Table1, growth on the pattern C and D are judged to be suitable for

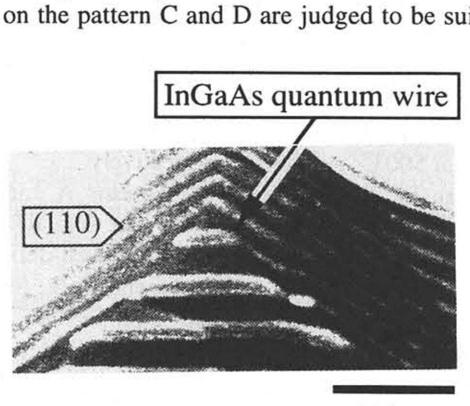


Fig.5 Successful wire formation using pattern D

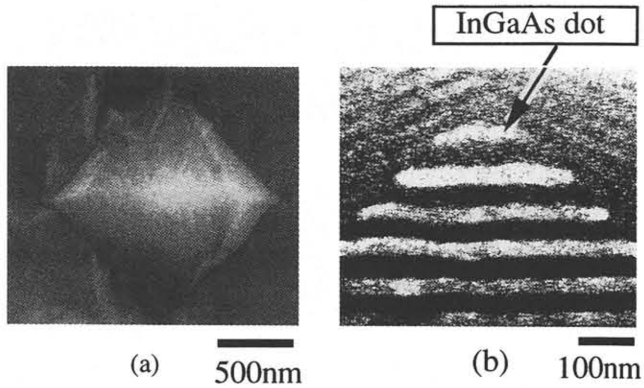


Fig.6 Successful dot formation using pattern G.

wire formation due to high structural uniformity and growth selectivity. Actually, InGaAs wire structures were successfully formed on patterns C and D. Figure 5 shows a cross-sectional SEM image of InGaAs wire grown on the pattern D at 550℃. An InGaAs wire with an apparent width of 110 nm is clearly seen on the InAlAs terrace. Since the cross-section was observed in Fig.5 from the <110> direction, which forms an angle of 45° with respect to the <100> wire direction, the actual wire width should be 80 nm. Details of wire formation on pattern C were presented elsewhere.[6]

3.3 Results on Dot Formation

The growth result on dot formation at T_g=500°C is summarized in Table 2. In all the dot structures tried, characteristic (421) facets appeared on the top together with other facets. From the viewpoint of structural uniformity and growth selectivity, the best pattern for dot formation was found to be the pattern G with (201) side-wall facets. Figure 6 shows the plan-view and cross-sectional SEM micrographs of the InGaAs quantum dot formed on the pattern G. Successful formation of dots with the side length of 100 nm can be recognized on the top portion of Fig. 6(b).

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