Toward nano-metal buried structure in InP – 20 nm wire and InP buried growth of tungsten

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Abstract

Toward nano-metal buried structure in InP, we studied the fabrication process of nano-tungsten wire and the InP buried growth of tungsten stripes. A tungsten wire with a 20 nm width was fabricated by the proposed metal-stencil liftoff, in which gold/chromium and SiO\textsubscript{2} replace resist to prevent thermal deformation in a conventional liftoff process. The buried growth of tungsten stripes with 1 \(\mu\text{m}\) widths and 2 \(\mu\text{m}\) pitch by organometallic vapor phase epitaxy (OMVPE) was studied. Tungsten stripes were buried under the flat InP layer of 1.1 \(\mu\text{m}\) thickness, and the ratio of grown InP thickness to buried tungsten width was about 1. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Metal has the advantages of high carrier concentration and low resistivity over semiconductors. These advantages would be more significant in reducing the device size. Metal nano-structures buried in semiconductors would be used as contact to semiconductors and control gate of depletion layer in new electron devices. As such new devices, we proposed a solid state biprism device [1] and buried metal heterojunction bipolar transistor [2]. Previously GaAs overgrowth of tungsten wires by OMVPE was published [3,4]. However, GaInAs/InP-based system has the advantage of electronic properties over GaAs-based system, such as high electron mobility and large \(\Gamma\)--\(L\) intervalley separation. Then, we selected a GaInAs/InP-based system as semiconductor materials. To fabricate these devices, the formation of tungsten wire with several 10 nm width and study of buried growth by InP using OMVPE are required. However, no InP overgrowth of tungsten is reported.
In this report, fabrication processes for metal nanostructures buried in InP are reported. The tungsten wire with a 20 nm width was fabricated by the proposed metal-stencil liftoff. In the buried growth of tungsten stripes, tungsten was buried with a flat InP layer and the ratio of grown InP thickness to buried tungsten width was about 1.

2. Fabrication of tungsten wire

The necessary conditions for metal buried in semiconductors is no formation of alloyed metal at growth temperature of OMVPE. We selected tungsten as the buried metal because the stability of tungsten in OMVPE growth was confirmed [5]. The problem of fabrication in tungsten fine patterns by use of a conventional liftoff method is thermal damage of a resist in evaporation of tungsten. To make a fine pattern, we used electron beam lithography with PMMA resist. Due to poor thermal durability of PMMA, the problem of thermal damage becomes more severe. At first, we used cooling of the sample holder in the evaporator until 0°C. However, the minimum width of formed tungsten wire was limited to 500 nm in case of simple PMMA liftoff.

To overcome the difficulty, the metal-stencil liftoff using gold/chromium (Au/Cr) and SiO₂ is proposed. Fig. 1 shows a schematic view of the metal-stencil liftoff process. At first, a 100 nm thick SiO₂ is deposited by chemical vapor deposition on an InP substrate. Then, Au/Cr patterns on SiO₂ is formed by liftoff and evaporation as metal-stencil. Several 10 nm separation of Au/Cr patterns becomes a fine slit, as shown in Fig. 1(a). Next, SiO₂ under the slit is etched by BHF to expose InP surface. At the same time, undercut etching makes a gap under the stencil for easy liftoff, as shown in Fig. 1(b). The negative stencil pattern is transferred onto the substrate by evaporation of tungsten. The width of tungsten is equal to the width of the stencil slit, and the width of stencil slit is decreased by deposition of tungsten around the slit. As a result, the cross-section of the tungsten wire becomes trapezoidal and the height of the tungsten wire is limited by the width of the stencil slit, as shown in Fig. 1(c). Finally, the metal-stencil with the deposited tungsten is etched away by liftoff process in BHF and a fine tungsten wire is formed on the substrate, as shown in Fig. 1(d).

Fig. 2 shows the SEM image of a 20 nm wide tungsten wire fabricated by the metal-stencil liftoff. The
width fluctuation of formed tungsten wire was less than 10 nm. Discontinuity, which is a serious problem in the fabrication of nm-size electrodes, was not formed in the top view of a SEM image.

In the metal-stencil liftoff, the space between tungsten patterns or the size of Au/Cr patterns was limited so that Au/Cr patterns can be removed by the BHF etching. To overcome this limitation and make an arbitrary pattern, we combined liftoff by PMMA with metal-stencil liftoff. Fig. 3(a) shows a schematic cross-section of the combined liftoff process. At first, metal-stencil for liftoff of fine pattern was formed and SiO$_2$ was etched by the same process, as shown in Fig. 1(a)–(c). Next, larger patterns were formed by PMMA resist aligned with stencil. Then, tungsten was evaporated on the sample. PMMA resist with the deposited tungsten was removed by liftoff in acetone and metal-stencil with the deposited tungsten was removed by liftoff in BHF. Fig. 3(b) shows the tungsten wire with a 30 nm width and a 1 μm length formed by the combined liftoff process.

3. InP growth burying tungsten wire

To bury tungsten with InP for the device application, the growth must satisfy the following requirements. The burying InP must be a single crystal. Thus, lateral overgrowth from the window region is essential. Provided that the top surface is flat, thinner overgrown layer is preferable. No formation of a void in the burying material was also required.

To find growth conditions applicable to the buried growth, the cross-sectional shape grown from the stripe window was observed. To prevent the formation of a void, the facet of lateral growth must have an acutely angled facet, as shown in Fig. 4(a). If laterally grown facets have obtuse angles, they meet at the center of the stripe to make a void, as shown in Fig. 4(b).

To be buried under a thinner layer, the ratio of thickness-to-width of a grown mesa in the window region was the figure of merit. Lower thickness/width ratio will realize buried growth with a thinner layer. We paid attention to the facet angle and thickness/width ratio in observation of the cross-sectional view of the lateral grown region.

Fig. 5 shows the schematic view of the sample structure with tungsten stripes for the observation of the facet of lateral growth. Four different stripe directions that were 0°, 30°, 45° and 90° from (0 1 1) direction were fabricated. The pitch and width of the
Fig. 5. Schematic view of tungsten stripes with 1 μm width and 2 μm pitch. Four types of samples were used for the experiment. Angles of stripes from (011) direction were 0°, 30°, 45° and 90°.

tungsten wires were 2 and 1 μm, respectively. The stripe pattern of a 30 nm thick tungsten was formed on a (100) InP substrate by photolithography and conventional liftoff process. A 500 nm thick InP layer was grown on these samples. Because the growth rate with tungsten wires was different from unpatterned substrate, the growth rate was defined by the unpatterned substrate. As growth conditions, we observed the dependence on growth temperature, V/III ratio and growth rate.

When the growth temperature was changed from 550°C to 650°C, the lower growth temperature provided a lower thickness/width ratio. However, the facet of the overgrown layer was unstable when growth temperature was 550°C. Thus, we set 600°C as the growth temperature in the following experiments.

Dependence on V/III ratio was shown in Fig. 6(a) when the stripe directions were 30° or 45°. The growth rate was kept at 14 nm/min. Where open marks show the layers with obtuse-angled facet while solid marks show the layers without an obtuse angled facet. Higher V/III ratio provided a lower thickness/width ratio. When the stripe direction was 0° or 90°, a facet without an obtuse angle was not observed, although the dependence of the thickness/width ratio on the V/III ratio was similar to stripes with a direction of 30° or 45°.

Dependence on growth rate is shown in Fig. 6(b) when the stripe directions were 30° or 45°. From Fig. 6(a), higher V/III ratio was preferable for lower thickness/width ratio. However, when we changed the growth rate by the change of flow rate of trimethylindium (TMI), available range of V/III (PH3/TMI) ratio was limited by the apparatus.

To get better results, the flow rate of PH3 in Fig. 6(b) was kept at the highest value ($2.23 \times 10^{-2}$ mol/min) of the apparatus. A higher growth rate provided a lower thickness/width ratio, as shown in Fig. 6(b). When the growth rate was 28 nm/min, both of the stripes along the 30° direction and the 45° direction had no obtusely angled facet. When the stripe direction was 0° or 90°, a facet without obtuse angle was
Fig. 7. Cross-sectional SEM view of tungsten stripes after buried growth. (a) Stripe direction was 30° from \( \langle 0 \, 1 \, 1 \rangle \) direction. Measured thickness of grown InP layer was 1.1 \( \mu \)m. (b) Stripe direction was 45°. Tungsten was buried by InP layer with no void but InP top surface was not flat.

not observed, although the dependence of the thickness/width ratio on V/III ratio was similar to stripes with directions of 30° or 45°.

To confirm embedding tungsten stripes by a flat layer, the thickness of InP was changed to 1.0 \( \mu \)m under 600°C as growth temperature, 460 as V/III ratio and 28 nm/min as growth rate. Fig. 7(a) shows a cross-sectional SEM view of tungsten stripes after the buried growth when stripe direction was 30°. Complete embedding by a InP layer with flat top surface and no formation of voids was observed. Measured thickness of InP was 1.1 \( \mu \)m. The ratio of the grown InP thickness to the buried tungsten width became about 1. Fig. 7(b) shows the stripe along the 45° direction. The tungsten surface was covered by a InP layer without a void, but the top surface of overgrown InP was not flat. When the stripe direction was 0°, a void on the stripe was observed.

Lateral growth rate of GaAs on the sample having round mesa without tungsten mask increased with low growth temperature and high As partial pressure, and flow rate of trimethylgallium had no influence on the ratio of lateral to vertical growth rate [6]. In our results, growth temperature and V/III ratio had the same dependence. However, lateral growth was also affected by flow rate of TMI. We thought that the reacting species decomposed on tungsten surface enhanced lateral growth, and we need additional consideration.

4. Conclusion

In order to fabricate nano-metal buried in an InP structure, the fabrication of a fine tungsten wire and InP buried growth of tungsten stripes were studied. A 20 nm wide tungsten wire was fabricated by the metal-stencil liftoff, in which gold/chromium and SiO\(_2\) replace resist. The buried growth of tungsten stripes was studied to obtain suitable growth conditions. Tungsten stripes with 1 \( \mu \)m width and 2 \( \mu \)m pitch was embedded by 1.1 \( \mu \)m thick InP flat layer, and the ratio of the grown InP thickness to the buried tungsten width became about 1. The buried metal structure, consisting of a 20 nm wide tungsten wire buried in a 20 nm thick InP, would be fabricated by a combination process of metal-stencil liftoff and buried growth.

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