Fabrication and transport properties of 50-nm-wide Au/Cr/GaInAs electrode for electron wave interference device

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Abstract

To conduct Young’s double slit experiment using a semiconductor, fabrication techniques for 80 to 100-nm-period fine electrodes with 30 to 40-nm thickness are reported. To obtain a resist pattern suitable for the lift-process, we used a double-layer resist with ZEP-520 and PMMA. The mixing of C60 into both layers and rinsing by perfluorohexane (PFH) prevented pattern collapse. As a result, a Au/Cr pattern with a 80-nm period over 30-nm steps was obtained. Using the developed process, we fabricated a device for observing the interference pattern. Unfortunately, the collector current from each electrode was not uniform. Moreover, the current showed anomalous behavior. The current occasionally converged in two different points and sudden jumps from the lower converged point to the upper converged point were also observed in time-dependent measurements. Such anomalous behavior might be explained in terms of a change in the ionization of an impurity near the metal–semiconductor interface. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The lateral wave property of a hot electron in a semiconductor has the possibility to provide a principle for new devices because of the high speed of hot electrons and the functionality of the wave property [1]. To confirm the wave property based on an interference characteristic, we proposed a device for Young’s double slit experiment using a semiconductor [2]. In the devices, hot electrons in the semiconductor are modulated by a buried double slit in which the slit spacing is close to the wavelength of the hot electrons and an interference pattern between the hot electrons from different slits is observed by using multiple fine electrodes. In the devices, the product of the slit spacing and the pitch of electrodes must be lower than 2000 nm² due to the scattering of hot electrons.

Recently, we reported a 25-nm-pitch InP/GaInAs buried grating, using a calixarene resist [3]. Thus, the required period for electrodes became 80 nm. Previously, we reported 100-nm-period electrodes [4] with 20-nm thickness. We used 20-nm-thick SiO₂ as the insulating layer in this experiment. However, many disconnections were observed when electrodes crossed the 20-nm-high step of contact windows.

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Moreover, the SiO$_2$ layer was not suitable as the insulating layer of the devices due to leakage current [5]. Changing the insulating layer usually results in an increase of thickness. Therefore, thicker fine electrodes must be developed to achieve reliable interconnection.

In this paper, we report the fabrication techniques for 80 to 100-nm-period fine electrodes with 30 to 40-nm thickness. An anomalous current behavior observed in the fabricated devices is also reported.

2. Formation of fine electrode

To obtain a high aspect ratio of electrodes by the lift-off process, resist patterns with high aspect ratios and vertical facets are essential. To realize the pattern suitable for lift-off, we used a double-layer resist system. As the top layer of the double-layer resist, we used ZEP-520 containing fullerene (C$_{60}$) (ZEP-520@C$_{60}$) [6] because of its high dry-etching resistance and mechanical strength. In the double-layer resist with ZEP-520@C$_{60}$, a pure ZEP-520 layer has been reported as the underlayer [7]. However, a ZEP-520 layer does not have good adhesion with a GaInAs layer or our insulating layer benzocyclobutene, BCB. To attach BCB and GaInAs, we used a PMMA layer as the underlayer. By using an adhesion promoter (hexamethyldisilazane), a ZEP-520@C$_{60}$ layer can be spun on to the PMMA layer.

In order to obtain a vertical facet in the developed resist patterns with a high aspect ratio, the thickness of the PMMA layer becomes important. A schematic of the pattern dependence on the thickness of PMMA is shown in Fig. 1. In the case of a PMMA single layer, the unexposed upper region of PMMA is dissolved within the required time for the dissolution of an exposed area, resulting in a trapezoidal pattern. When the single layer is thick, the bottom width becomes narrow due to insufficient time for dissolution. On the other hand, ZEP-520@C$_{60}$ has a dissolution-inhibiting effect [8]. Moreover, we can expect that dissolution of the upper region of the PMMA layer becomes slow due to the adjacent ZEP-520@C$_{60}$ layer in the double-layer resist. Thus, the dissolution of the unexposed area of the double-layer resist is slower than that of a single PMMA layer, resulting in a vertical facet of the resist pattern.

A higher aspect ratio can be obtained by using a thicker PMMA layer. However, when the PMMA layer is too thick, insufficient dissolution results in a trapezoidal pattern.

Fig. 2 shows a 100-nm-period resist pattern formed using the bilayer resist systems when the conditions were the same as above, except for the thickness of the PMMA layers. The amount of C$_{60}$ in ZEP-520@C$_{60}$ was 5 wt.%. The thickness of ZEP-520@C$_{60}$ was 35 nm. The acceleration voltage of the electron beam was 50 kV. Exposure doses were 3.0 nC/cm$^2$. The exposed sample was developed in a solution of methyl isobutyl ketone:isopropanol (IPA) = 1:3 for 45 s followed by rinsing in IPA for 15 s. Thicknesses of the PMMA layers in Fig. 2(a) and (b) were 90 and 80 nm, respectively. By changing the thickness of the PMMA layer, patterns were changed from trapezoidal to rectangular.

Another advantage of ZEP-520@C$_{60}$ is reformation by dry etching after the development, due to high dry-etching resistance. An almost vertical facet could be obtained by oxygen reactive ion etching (O$_2$, RIE) even though the shape became poor, as shown in Fig. 2(a). The typical conditions of O$_2$ RIE required to improve the shape were 10 Pa, 0.04 W/cm$^2$ and 60 s for pressure, power density and etching time, respectively.
To make a fine metal pattern, a resist pattern with an 80-nm period was formed under the conditions used in the case of Fig. 2(b), followed by slight O$_2$ RIE (10 Pa, 0.04 W/cm$^2$, 10 s) to remove the scum from the bottom. Fig. 3 shows a fine metal pattern (Au 30 nm/Cr 10 nm) after lift-off using the 80-nm-period resist pattern. A clear metal pattern was confirmed.

To apply the electrodes to the devices, we must make the electrodes on the step for contact windows. Fine electrodes were formed on a GaInAs collector mesa (width: 1.4 μm, height: 215 nm) with a contact window. For isolation, we used a 300-nm-thick BCB layer. The surface of BCB became flat after 1 h of baking at 200°C and the thickness of the BCB layer on the mesa became about 100 nm. Then the contact window was opened by RIE with a 600-nm-thick ZEP-520/80-nm-thick PMMA bilayer resist as an etching mask. Here, the PMMA layer acted as an adhesive layer. The etching conditions of RIE required to obtain a tilted etched facet of BCB were studied because an angled facet is effective in preventing disconnection of electrodes. The etched facet of BCB with an angle of 60° was obtained, as shown in Fig. 4(a), when the conditions of RIE were CF$_4$:O$_2$ = 9:1, 133 Pa, 0.4 W/cm$^2$ and 2 min for gases, pressure, power density and etching time, respectively. We attempted to make 100-nm-period electrodes (thickness: Au 20 nm/Cr 10 nm) on the step under the conditions used in the case of Fig. 3. An SEM view after lift-off is shown in Fig. 4(b). Some lines became wide and many breaks were observed. These could be explained by the collapse of the resist pattern at the step.

Pattern collapse is a typical problem of a resist pattern with a high aspect ratio. Because collapse occurs due to surface tension of the rinsing solution in the drying process, the rinser was changed from IPA to PFH to reduce the surface tension [9]. The developer was also changed to xylene. Changing of the rinser reduced the possibility of pattern collapse, but this improvement was not sufficient to prevent the collapse on the step. Although a typical pattern collapse originates from the bottom of the pattern without deformation of the pattern itself [9], our pattern collapse originated from bending at the middle of the underlayer, as shown in Fig. 5(a). Thus, mechanical weakness of the underlayer caused the pattern collapse. To increase the mechanical strength,
C_{60} was incorporated into PMMA at 5 wt.%. As a result, a great reduction of the possibility of pattern collapse was confirmed, and bending at the middle of the layer was not observed even if collapse was observed, as shown in Fig. 5(b).

By using a bilayer resist in which C_{60} was incorporated in both layers, 80-nm-period electrodes on the step were formed. The height of the step was reduced to about 30 nm by applying slight RIE just before the formation of electrodes. The underlayer was a 80-nm-thick PMMA layer with C_{60} and the top layer was a 35-nm-thick ZEP-520@C_{60} layer. The line dose was 3 nC/cm. The developing time in xylene was 10 s while the rinsing time in PFH was 30 s. After O_{2} RIE (10 Pa, 0.04 W/cm² and 20 s), a 20-nm-thick Au layer and a 10-nm-thick Cr layer were evaporated. A top view of the electrodes by SEM is shown in Fig. 6. A clear metal pattern over the step was confirmed.

The contact characteristics were measured at 4.2 K. Seven 80-nm-pitch electrodes were formed on one collector mesa, and the inner five electrodes were measured. The mesa consisted of an n-GaInAs contact layer (thickness: 15 nm, ND: 2 × 10^{19} cm^{-3}), i-GaInAs transit layer (thickness: 200 nm) and i-InP barrier layer (thickness: 10 nm). Fig. 7 shows the typical voltage–resistance characteristics between two electrodes when the two electrodes are located side by side. Two series from two different mesas are shown in Fig. 7. We believe that there was no disconnection or short circuit in all measured electrodes because the measured values were in a moderate range. Weak dependence of resistances on ap-

Fig. 4. (a) Cross-sectional view of BCB contact window on collector mesa. Etched facet of BCB with an angle of 60° can be observed. This image shows the test structure; the thickness of BCB was 530 nm. (b) SEM view after lift-off in the attempt to fabricate electrodes on the step of the contact window. The brighter rounded region was the GaInAs window while the darker region was BCB. The nominal period was 80 nm.

Fig. 5. (a) Typical resist pattern collapse of ZEP-520@C_{60} / PMMA double-layer system. (b) Typical resist pattern collapse of ZEP-520@C_{60} / PMMA@C_{60} double-layer system.
applied voltage indicated Ohmic characteristics, although a large difference in the resistance between each electrode was also observed. The nominal area of the electrode was $1 \times 10^{-9}$ cm$^2$ ($40$ nm $\times 2.5$ \mu m) and the estimated contact resistance was in the range between $10^{-3}$ and $10^{-5}$ $\Omega$ cm$^2$ when we assumed that the resistance depended on the contacts.

Local oxidation of the GaInAs surface is a probable reason for the observed large difference in contact resistance, because the surface treatment just before the evaporation was O$_2$ RIE. For the improvement of the uniformity, removal of the oxide or development of an alloying contact with a shallow junction [10] would be required. Although a higher carrier concentration of the n-GaInAs layer would improve the contact, the lowering of the sheet resistance of the top layer results in the distribution of the current from the peak of the interference to many electrodes. Therefore, shallow RIE of the top layer with electrodes as a mask would also be required to increase the resistance between electrodes.

3. Fabrication and measurement of the device

By combining the described process for electrodes and a process for buried slits [3], we fabricated devices to observe the interference pattern. A schematic cross-sectional view of the devices is shown in Fig. 8. The differences from the former device operated under a magnetic field [11] are: (1) a reduction of the slit spacing (40 nm $\gg$ 25 nm), (2) an increase in the number of collector electrodes ($2 \gg 7$), and (3) a different insulating layer. To reduce the large leakage currents obtained in Ref. [11], the insulating layer was changed from SiO$_2$, which caused many leakage paths [5], to BCB. A top SEM view of the device is shown in Fig. 9. The thicknesses, the width and the period of the collector electrodes were Au 20 nm/Cr 10 nm, 50 nm, and 100 nm, respectively. The length of the collector
contacts was 2.5 μm. The graded emitter was designed for a bias of 0.1 V between the base and the emitter.

When 0.1 V was applied between the base and the emitter, the collector current was measured at 4.2 and 77 K. The potential between the base and the collectors was kept at zero. The observed collector currents were lower than the base current due to the reduction of leakage. However, the difference between each of the collector currents reached two orders of magnitude. Moreover, anomalous behavior of the collector current prevents accurate measurement.

Fig. 10 shows the time–current characteristics obtained by 15 60-s measurements from one collector electrode at 4.2 K. The current occasionally converged at 1.3 or 1.38 μA. The fluctuation after the conversion was around 0.01 μA. A sudden jump from the lower converged point to the upper converged point was also observed. Although the result in Fig. 10 shows one jump, two jumps from the lower converged point to the upper converged point were also observed in the other electrode. Thus, the jump is reproducible. Since we did not observe the current conversions into two different points at 77 K, the anomalous behavior occurred only at low temperatures such as 4.2 K. However, raising the temperature not only results in an increase of scattering, but widens the lateral energy distribution of hot electrons [12].

The anomalous current behavior might be explained as the follows. Ohmic contact at low temperature is based on tunneling-dominated transport in the Schottky barrier [13], where the tunneling probability is strongly dependent on the thickness of the depletion region. Because of local oxidation and the small nominal area of one electrode (50 nm × 2.5 μm), we can infer that the actual contact area was divided into many small paths. If the area of one current path is so small that the depletion layer is decided by one impurity, the ionization change of the impurity drastically changes the tunneling probability. For example, when one impurity near a metal–semiconductor interface is changed from a neutral one to an ionized one, thickness of the tunneling barrier decreases, resulting in the appearance of a new effective path.

Fig. 10. The time–current characteristics obtained by 15 60-s measurements from one collector electrode. Temperature was 4.2 K.
4. Summary

To conduct Young’s double slit experiment using a semiconductor, fabrication techniques for 80 to 100-nm-period fine electrodes with 30 to 40-nm height are reported. To obtain a resist pattern suitable for the lift-off process, we used a double-layer resist with ZEP-520 and PMMA. On a flat surface, we could obtain a Au/Cr pattern with an 80-nm period and 40-nm thickness. When electrodes crossed the 30-nm step, a Au/Cr pattern with an 80-nm period and 30-nm thickness could be fabricated. The mixing of C$_{60}$ into both layers and rinsing by PFH were effective in preventing pattern collapse.

Using the developed processes, we fabricated the device to observe the interference pattern. Unfortunately, the collector currents from each electrode were not uniform. Moreover, the current showed anomalous behavior. The anomalous behavior might be explained in terms of the change in the ionization of one impurity near the metal–semiconductor interface.

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