High Temperature Growth of GaP on Si Substrates by Metalorganic Vapor Phase Epitaxy

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GaP was grown on misoriented Si substrates using metalorganic vapor phase epitaxy (MOVPE). At 700 and 800°C no mirror surface was obtained. A mirror surface was achieved at 830°C with a high PH_3 flow rate. The island nucleation density at the initial growth stage increased with temperature between 700 and 800°C and saturated beyond 800°C. Islands with the density of $10^{11}cm^{-2}$ nucleated at 830°C. Cross-sectional transmission electron microscopy (c-TEM) shows 5-nm thick GaP layer was formed by coalescence of the islands at 830°C. A cross-hatched pattern (CHP) was observed for a 200-nm thick GaP layer grown at 830°C. The CHP indicates that the quality of the GaP layer was high. Cross-sectional TEM reveals that few stacking faults and dislocations

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exist in 5-nm and 40-nm thick GaP layers on Si substrates.

KEYWORDS: GaP on Si, metalorganic vapor phase epitaxy, PH_3 flow rate, growth pressure, nucleation density, cross-hatched pattern, heteroepitaxy, growth mechanism

1. Introduction

III-V-N alloy semiconductors such as GaPN, InGaPN and InGaAsN materials can be lattice matched to Si material. A dislocation-free GaPN/Si was realized using solid source molecular beam epitaxy (MBE) .[1,2] Intense PL was obtained in GaAsPN on GaP substrates[3] and InGaPN on GaP substrates[4] grown with metalorganic vapor phase epitaxy (MOVPE). The GaPN epilayers were grown on GaP substrates using gas-source MBE, showing intense PL intensity.[5] Therefore, the GaPN on Si is attractive for monolithic integration of Si based electronic devices and optical devices using III-V-N compound semiconductors. Optoelectronic integrated circuits (OEICs) have been realized using GaPN layers on Si.[6,7] Nitridation of Si surfaces occurs during direct growth of GaPN layers on Si substrates, degrading the GaPN layers. For the GaPN layer on the Si substrate, a thin GaP layer without crystalline defects is required on the Si substrate.[1,2]

Several researchers have conducted two-step growth for high-quality GaP layers on Si substrates.[8,9] Low-temperature growth is effective for a smooth surface.[10,11] But stacking faults appeared at low temperature., which degraded layers[10,12] Growth of GaP/Si is reported to be a still challenging task.[13,14] Reportedly, migration enhanced epitaxy at low temperature yields a smooth surface layer without dislocations,[15] which is a promising result. This method, however, is not readily applicable to growth using MOVPE. Little attention has been paid to growth at temperatures above 700°C, which is a typical growth temperature for GaP, because three-dimensional island growth is believed to occur when using heteroepitaxy at high temperatures. However, growth at

900°C with an extensively high V/III ratio, 1600, using MOVPE was reported to result in smooth and high-quality GaP layers on Si substrates.[16,17,18] These results indicate that a GaP layer that is free from dislocations might be obtained at temperatures above 700°C below a critical thickness. The lattice mismatch between GaP and Si is 0.37%, which is as small as that between GaAs and Ge of 0.07%. Smooth GaAs layers with few defects were obtained on Ge substrates without addressing low temperature growth using MOVPE.[19] Therefore, we investigated the surface morphology of GaP layers grown on Si substrates at high temperatures above 700°C using MOVPE as a function of reactor pressure and source-gas flow rates.

2. Experimental

Epilayers of GaP were prepared using a MOVPE on Si(100) substrates with 4° misorientation toward [011]. The MOVPE reactor was a horizontal cold-wall type. Triethylgallium (TEG), and PH_3 were used as source materials. The reactor pressure was 100 or 300 Torr. The substrates were degreased and etched using a method described by Ishizaka and Shiraki.[20] They were preheated at 925°C in a H_2 flow for 30 min. The substrates were cooled down to a growth temperature of 700–830°C. They were exposed to PH_3 for 2 min before GaP growth initiation. Growth was initiated by TEG supply. The flow rates of source materials for GaP growth are listed in Table I. The total gas flow rate was 8.9×10^{-2} mol/min. The typical TEG flow rate and growth time were 3.5 μmol/min and 20 min, respectively. The layers were characterized using Nomarski interference microscopy, secondary electron microscopy (SEM) and atomic force microscopy (AFM). The structure was characterized using transmission electron

microscopy (TEM) operating at an acceleration voltage of 200 kV. Specimens for cross-sectional TEM observation were prepared by mechanical grinding followed by Ar^+ -ion bombardment.

3. Results and Discussion

Figure 1 shows surface morphologies investigated using SEM for GaP grown at 700°C with the PH_3 flow rates of 450 and 1350 μmol/min and growth pressures of 100 and 300 Torr. Large islands of lateral size of ~2 μm were observed at the PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr (sample a). The island density was 3 × 10^7 cm^{-2}. The total island density increased to 1.3 × 10^8 cm^{-2} (sample b) when the PH_3 flow rate increased to 1350 μmol/min. Islands with lateral size above 1μm, between which small islands with lateral size of 200 nm existed, were observed. The densities of the large island and small island were 6 × 10^7 and 7 × 10^7 cm^{-2}, respectively. Large islands and small ones were also observed at PH_3 flow rate of 450 μmol/min under growth pressure of 300 Torr (sample c). The large island density and small island density were 3× 10^7 and 1.3 × 10^8 cm^{-2}, respectively. For sample d grown with PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr, the densities of large island and small one were 5× 10^7 cm^{-2} and 2.5 × 10^8 cm^{-2}, respectively. The total island density of 3.0 × 10^8 cm^{-2} was larger than those of the samples grown under the other growth conditions at 700°C.

Figure 2 presents surface morphologies investigated using SEM for GaP grown at 800°C. Figure 2(a) shows the surface morphology for GaP with a PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr (sample e). Some islands collided with the

others. Compared to sample a, the area uncovered by the islands decreased by increasing temperature from 700 to 800°C. The island density was 1.9×10^8 cm^{-2}, which was higher than that of sample a. Figure 2(b) is the morphology of the sample prepared at 800°C with the PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr (sample f). The dark parts correspond to holes. A layer with a rough surface where small holes existed was obtained. The rough surface suggests that the layer was formed by coalescence of large islands that had nucleated initially on the Si surface. Coalescence of the islands might have been in progress, which left several holes in the layer. The hole density was 1.5×10^8 cm^{-2}.

Figure 2(c) shows the morphology of the sample prepared with PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr (sample g). A layer with small roughness was observed. A cross-hatched pattern (CHP) was observed in the sample periphery. The CHP indicates that the layer thickness in the periphery was greater than the critical layer thickness. The pattern means that misfit dislocations might be elongated on the interface between the GaP layer and the Si substrate toward the (011) direction without being blocked by preexisting defects such as stacking faults. The pattern suggests that the layer contained few defects in the periphery during growth below the critical layer thickness. Figure 2(d) is the surface morphology of the sample prepared with PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr (sample h). The surface was relatively smooth.

Figure 3 shows AFM images of the samples grown at 800°C under growth pressure of 300 Torr. Sample g shown in Fig. 3(a), the SEM image of which is shown in

Fig. 2(c), was grown with the PH_3 flow rate of 450 μmol/min. The Si surface was covered with islands, most of which mutually collided. The root-mean-square (rms) surface roughness value was 17 nm. Figure 3(b) shows an AFM image of sample h prepared with PH_3 flow rate of 1350 μmol/min. The SEM image of the sample is shown in Fig. 2(d). The Si surface seems to be covered with islands. The rms surface roughness value of sample h was 11nm. It decreased by 38% with increased PH_3 flow rate.

Figure 4 shows surface morphologies investigated with SEM for layers grown at 830°C. Figure 4(a) shows the surface morphology for the layer with PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr (sample i). A flat GaP surface was observed locally. The morphology suggests that the structures were rectangular solids with (100) top surface and (110) sidewalls. The height and width are around 100 and 1000 nm, respectively. A fraction of Si surface remained uncovered by GaP. Figure 4(b) shows an image of the sample prepared with the PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr (sample j). The GaP covered the whole Si surface. A fraction of the GaP surface shows the CHP, whereas the rest of the surface was slightly rough. Figure 4(c) shows a surface morphology of the sample prepared with the PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr (sample k). A layer with small roughness was observed. A CHP was observed in the periphery of the sample (not shown). Figure 2(d) is the surface morphology of the sample prepared with a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr (sample l). A layer with small roughness was observed.

Figure 5 shows AFM images of samples k and l grown at 830°C under growth

pressure of 300 Torr. Sample k shown in Fig. 5(a) was grown with the PH_3 flow rate of 450 μmol/min. The SEM image is shown in Fig. 4(c). The AFM image shows that a GaP layer was formed, the rms surface roughness of which was 9.3 nm. Figure 5(b) shows an AFM image of sample l prepared with PH_3 flow rate of 1350 μmol/min. The SEM image of the sample is shown in Fig. 4(d). The AFM image indicates that GaP covered the whole Si surface, the rms surface roughness of which was 2.6 nm. The smooth layer was partly observed. The image suggests that many small islands nucleated at the initial growth. Under this growth condition, transition from islands to a layer should occur at a smaller thickness compared to the other growth conditions because of the high nucleation density.

Island-like structures were observed at 700°C. Island-coalescence proceeded at 800°C and island-like structure disappeared at 830°C for 20-min growth. For evaluation of the island density at the initial growth stage, GaP was grown on Si substrates for 4 min at 800 and 830°C. The island density was estimated using AFM. Figure 6 shows the island density as a function of growth temperature. The island density increased with temperature between 700-800°C, whereas it seemed to saturate above 800°C. It increased with growth pressure at all temperatures. It increased with PH_3 flow rate except the sample grown at 830°C with growth pressure of 300 Torr. The respective island densities as large as 9.0×10^{10} and 8.8×10^{10} cm^{-2} were obtained for PH_3 flow rates of 450 and 1350 μmol/min at 830°C with growth pressure of 300 Torr. The typical island size was 20-40 nm in width and 2-4 nm in height at 830°C with 300 Torr. Therefore, islands partly coalesced each other, which might have resulted in

underestimation of the island density at 830°C with 300 Torr. The results for 20 min-growth indicate that the GaP surface became smoother with higher temperature, higher PH_3 flow rate and higher growth pressure. This should result from high island-density at the initial growth stage.

The layer was obtained for samples g and h at the periphery and samples j, k and l on the whole surface. The CHP was observed in samples g, h and k at the periphery. In sample j, the CHP was observed in a fraction of the sample in addition to the periphery. Sample l has a smooth surface with no CHP, which might result from the layer thickness being less than the critical thickness for dislocation introduction. The critical thickness of GaP on Si was suggested to be between 50 and 100 nm.[15] Therefore, the thickness of GaP layer was evaluated with AFM measurement of the samples where the GaP layer was partly removed by selective etching. The results for growth thickness are shown with GaP surface roughness in Table III. The sample l thickness is 25 nm, being less than the critical thickness.

The results indicate that the GaP surface became smoother with higher temperature, higher PH_3 flow rate and higher growth pressure. The trend is qualitatively similar to that reported.[16] It was reported that high-quality GaP was obtained at 900°C with a V/III ratio of 1600 and growth pressure of 380 Torr.[16] A high temperature was necessary for GaP layer on Si substrate. Decomposition of PH_3 enhanced by high temperature increases the concentration of P atoms on the surface, which might increase the probability of island nucleation as reported.[17] High-temperature growth was found to be attractive also in our apparatus. However, Table III suggests that the growth rate

will decrease further with increasing temperature because of GaP evaporation, which requires more growth time for the GaP layer. A high PH_3 flow rate is also expected to increase the concentration of P atoms on the surface. Therefore, growth at a PH_3 flow rate higher than 1350 μmol/min is also attractive.

Table III shows that the growth thickness was small for sample l where the smooth surface without the CHP was obtained. The CHP confirms that a layer is of high quality. The quality of sample l has never been determined. We increased the growth thickness over the critical thickness by increasing the growth rate to investigate the quality of GaP layers grown under growth conditions at 830°C with a high PH_3 flow rate and high growth pressure. To increase the growth rate we increased the TEG flow rate to 14 μmol/min with the PH_3 flow rate of 1350 or 2700 μmol/min. The V/III ratios were 97 and 193. The growth pressures were 100 and 300 Torr with various growth times. The higher Ga source flow rate is expected to increase the nucleation density as GaAs on Ge.[19] This expectation also derives from the fact that the CHP was observed in the periphery of samples g, h, j and k where the growth rate was larger than that in the middle of the samples.

Figure 7 shows surface morphologies of the layers grown under the above conditions. The surface morphologies were observed using Nomarski interference microscopy. Figure 7(a) shows the surface morphology of a layer with growth pressure of 100 Torr, the PH_3 flow rate of 1350 μmol/min and growth time of 20 min (sample m). A rough surface was observed in the middle of the sample. The CHP covered the whole surface as shown in Fig. 7(b) (sample n) when the PH_3 flow rate increased to 2700

μmol/min. Pit-like structures were observed in addition to the CHP pattern. Figure 7(c) shows the surface morphology of a layer with growth pressure of 300 Torr, the PH_3 flow rate of 1350 μmol/min and growth time of 40 min (sample o). The CHP covered the whole surface with several pits. Figure 7(d) shows the surface morphology of a layer with growth pressure of 300 Torr, the PH_3 flow rate of 2700 μmol/min and growth time of 60 min (sample p). The CHP covered the whole surface with few pits. The results indicate that the growth at 830°C with the PH_3 flow rate of 2700 μmol/min, the TEG flow rate of 14 μmol/min and growth pressure of 300 Torr resulted in a high-quality GaP layer on the Si substrate. The result is attractive because no CHP has been reported for GaP layers on Si substrates prepared using MOVPE with TEG and PH_3. The layer thickness was 200 nm. Figure 7(e) shows the surface morphology of a layer grown using the above growth conditions for 20 min. The layer thickness was 40 nm, which was below the critical thickness. A specular layer was observed. Surface morphology depended qualitatively on the growth pressure and PH_3 flow rate, as reported.[16] In our growth, however, a lower PH_3 flow rate and lower growth temperature were required for flat GaP layers on Si substrates compared to the reported values. This might be because we used TEG, whereas the reported growth used trimethylgallium.

Also in our laboratory, several GaP layers were grown on Si substrates using TMG instead of TEG under the PH_3 flow rates of 450 and 1350 μmol/min with a growth pressure of 100 Torr and growth temperatures between 700 and 900°C. The morphology of the layers improved with PH_3 flow rate and temperature. The morphology, however, was far from a mirror surface. The result suggests that more PH_3

flow rate or higher growth pressure at 900°C will be required for a smooth GaP layer using TMG. We found for the first time that lowering the growth temperature for high-quality GaP layers on Si substrates below 900°C is possible by using TEG under the optimized growth conditions. TMG molecules are reported to decompose to monomethyl Ga (MMG) molecules that decompose to Ga atoms with aid of AsH_3 molecules. TEG molecules decompose to Ga atoms by β hydride elimination,[21] which require no AsH_3 molecules. For decomposition of TMG molecules to Ga atoms for GaP growth, TMG molecules might require PH_3 molecules, whereas TEG molecules require no PH_3 molecules for decomposition to Ga atoms. Thus, less PH_3 flow rate and lower temperature required for a flat GaP surface compared to the reported values might result from higher decomposition rate of TEG molecules. High decomposition rate of TEG might enhance GaP nucleation

Growth mechanism at 830°C with the PH_3 flow rate of 2700 μmol/min and growth pressure of 300 Torr was investigated using AFM images of samples with various thicknesses. Figure 8 shows surface morphologies of samples grown for (a) 1 min, (b) 6 min, (c) 12 min and (d) 20 min. The layer thickness of the sample grown for 20 min was 40 nm. For 1-min deposition, the island density was 7.0×10^{10} cm^{-2} and the islands covered almost of the substrate surface. The islands were circular, having sides with small slopes. The typical island size was 40 nm in width and 2-3 nm in height. For 6-min growth, the island density increased to 1×10^{11} cm^{-2}. The typical island width remained 40 nm, whereas the island height increased to 4-8 nm. The respective rms values were 0.46 and 1.1 nm for 1-min growth and 6-min growth. The results indicate

that islands grew mainly vertically, causing increased surface roughness. A Layer was obtained for 12-min growth, as shown in Fig. 8(c). The islands coalesced slowly between 6 and 12 min. The surface structure was elongated mainly parallel to the steps. Holes with lateral length of 50-100 nm and depth of 10-20 nm were observed. The hole density was 1.0×10^9 cm^{-2}. Figure 8(d) shows that smooth surface was obtained for 20-min growth. The hole density decreased to 3.0×10^8 cm^{-2}.

For 6-min growth, the most islands were elongated in direction of the steps as shown in Fig. 9(a). The large islands were surrounded with the faceted surfaces. Figure 9(b) is an enlarged AFM image of the surface for 6-min growth. The Figure shows that the sidewalls of the large islands parallel to the steps were (113) planes. The elongated island shape results from anisotropy in surface energy[22], indicating a low growth rate of (113) planes under the above growth conditions. Some islands were elongated vertically to the steps. These are antiphase domains (APDs).[22,23] In spite of using 4° misoriented substrate the antiphase domains were not completely eliminated. Fig. 9(c) shows that for 20-min growth the surface was smooth. Few structures indicating APDs was found.

Figure 10(a) shows cross-sectional TEM image of the sample grown for 12 min. TEM observation was performed using (220) conditions. A 5-nm thick layer covered the whole Si surface. Bunched step-like structures were observed on Si. Irradiation of PH_3 to Si surface for 2 min might roughen the surface as AsH_3 irradiation to Si surface.[24] Figure 10(b) shows a high resolution TEM image of the sample. The results indicate that no stacking faults and dislocations existed. No stacking faults and dislocations were found also in a 40-nm thick GaP layer on a Si substrate as shown in Fig. 10(c). The

results indicate that the growth conditions are useful as the buffer layer for GaPN. The critical thickness is above 40 nm. From 12 min to 20 min, the layer thickness was as small as 5 nm. In successive 8-min growth, the layer thickness increased from 5 to 40 nm. The growth rate of the layer was estimated to be 260 nm/h between 12 and 20 min. The islands observed at 1 and 6 min were found to grow extremely slowly under the above growth conditions. For APDs, further investigation will be required.

4. Conclusions

We prepared GaP on misoriented Si substrates using MOVPE. The surface morphology improved with increasing growth temperature above 700°C. The GaP surface became smoother with a higher PH_3 flow rate and a higher growth pressure. The GaP was grown at 830°C with TEG flow rate of 14 μmol/min and PH_3 flow rate of 2700 μmol/min under growth pressure of 300 Torr. A mirror surface was observed at 40-nm thickness, whereas a CHP was obtained at 200-nm thickness. The CHP indicates that the GaP layer contains few defects that block gliding of dislocation. AFM shows that islands with the density of $\sim 10^{11} cm^{-2}$ existed at the initial growth stage. Cross-sectional TEM reveals that 5-nm thick layer was formed. No stacking faults and threading dislocations were found in the layer.

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References

1) Y. Furukawa, H. Yonezu, K. Ojima, K. Samonji, Y. Fujimoto, K. Momose, and K. Aiki: Jpn. J. Appl. Phys. **41** (2002) 528.

2) Y. Fujimoto, H. Yonezu, A. Utsumi, K. Momose, and Y. Furukawa: Appl. Phys. Lett. **79** (2001) 1306.

3) S. Sanorpim, F. Nakajima, N. Nakadan, T. Kimura, R. Katayama, and K. Onabe: J. Cryst. Growth **275** (2005) e1017.

4) G. Biwa, H. Yaguchi, K. Onabe, and Y. Shiraki: J. Cryst. Growth **189/190** (1998) 485.

5) H. P. Xin, R. J. Welty, Y. G. Hong, and C. W. Tu: J. Cryst. Growth **227/228** (2001) 558.

6) Y. Furukawa, H. Yonezu, Y. Morisaki, S-Y. Moon, S. Ishiji, and A.Wakahara: Jpn. J. Appl. Phys. **45** (2006) L920.

7) Y. Furukawa, H. Yonezu, A. Wakahara, and S. Ishiji: S. Y. Moon, Y. Morisaki: J. Cryst. Growth **300** (2007) 172.

8) J. M. Olsen, M. M. Al-Jassim, A. Kibbler, and K. M. Jones: J. Cryst. Growth **77** (1986) 515.

9) M. Sadeghi and S. Wang: J. Cryst. Growth **227-228** (2001) 279.

10) S. J. Santana, C. R. Abernathy, S. J. Pearton, and K. S. Jones: J. Cryst. Growth **164** (1996) 248.

11) W. G. Bi, X. B. Mei, and C. W. Tu: J. Cryst. Growth **164** (1996) 256.

12) V. Narayanan, S. Mahajan, N. Sukidi, K. J. Bachmann, V. Woods, and N. Dietz:

Philos. Mag. **A 80** (2000) 555.

13)V. K. Dixit, T. Ganguli, T. K. Sharma, S. D. Singh, R. Kumar, S. Porwal, P. Tiwari, A. Ingale, and S. M. Oak: J. Cryst. Growth **310** (2008) 3428.

14)X. Liu, K. Kim, and D. E. Aspnes: J. Vac. Sci. Technol. **B25** (2007) 1448.

15) Y. Takagi, H. Yonezu, K. Samonji, T. Tsuji, and N. Ohshima: J. Cryst. Growth **187** (1998) 42.

16) T. Soga, T. Suzuki, M. Mori, T. Jimbo, and M. Umeno: J. Cryst. Growth **132** (1993) 134.

17) T. Soga, T. Jimbo, and M. Umeno: J. Cryst. Growth **146** (1995) 554.

18) T. Suzuki, M. Mori, Z. K. Jiang, T. Soga, T. Jimbo, and M. Umeno: Jpn. J. Appl. Phys. **31** (1992) 2079.

19) G. Timò, C. Flores, B. Bollani, D. Passoni, C. Bocchi, P. Franzosi, L. Lazzarini, and G. Salviati: J. Cryst. Growth **125** (1992) 440.

20) A. Ishizaka and Y. Shiraki: J. Electrochem. Soc. **133** (1986) 666.

21) A. C. Jones: J. Cryst. Growth **129** (1993) 728.

22) F. Ernst and P. Pirouz: J. Mater. Res. **4** (1989) 834.

23) S. F. Fang, K. Adomi, S. Iyer, H. Morkoç, H. Zabel, C. Choi, and N. Otsuka: J. Appl. Phys. **88** (1990) R31.

24)K. Asai, K. Fujita, and Y. Shiba: Jpn. J. Appl. Phys. **30** (1991) L1967.

Figure captions

Fig. 1. SEM images of GaP structures grown on Si substrates at 700°C: (a) with a PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr; (b) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr; (c) with a PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr; (d) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr.

Fig. 2. SEM images of GaP structures grown on Si substrates at 800°C: (a) with a PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr; (b) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr; (c) with a PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr; (d) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr.

Fig. 3. AFM images of the samples grown at 800°C: (a) with a PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr; (b) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr.

Fig. 4. SEM images of GaP structures grown on Si substrates at 830°C: (a) with a PH_3 flow rate of 450 μmol/min and growth pressure of 100 Torr; (b) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr; (c) with a PH_3 flow rate of 450 μmol/min and growth pressure of 300 Torr; (d) with a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr.

Fig. 5. AFM images of samples grown at 830°C under 300 Torr: (a) a PH_3 flow rate of 450 μmol/min; (b) a PH_3 flow rate of 1350 μmol/min.

Fig. 6. Island density for 4-min growth as a function of temperature. Closed symbols

and open symbols represent growth pressures of 100 and 300 Torr, respectively. Circles and triangles represent PH_3 flow rates of 450 and 1350 μmol/min, respectively.

Fig. 7. AFM imagess of samples grown at 830°C with a TEG flow rate of 14 μmol/min: (a) a PH_3 flow rate of 1350 μmol/min and growth pressure of 100 Torr; (b) a PH_3 flow rate of 2700 μmol/min and growth pressure of 100 Torr; (c) a PH_3 flow rate of 1350 μmol/min and growth pressure of 300 Torr; (d),(e) a PH_3 flow rate of 2700 μmol/min and growth pressure of 300 Torr. Growth times were 40, 40, 40, 60 and 20 min for (a), (b), (c), (d) and (e), respectively.

Fig. 8. AFM images of samples grown for (a) 1 min, (b) 6 min, (c) 12 min, (d) 20 min. Samples were grown at 830°C with a PH_3 flow rate of 2700 μmol/min and growth pressure of 300 Torr. The scan field is 1×1 μm^2. The vertical scale is 20 nm.

Fig. 9. AFM images of samples grown for 6 and 20 min. Samples were grown at 830°C with a PH_3 flow rate of 2700 μmol/min and growth pressure of 300 Torr. (a) An enlarged top view of surface for 6 min. Arrows indicate APDs. (b) An enlarged image of islands for 6 min. Vertical scale is 8 nm. (c) An enlarged top view of surface for 20 min. The scan field is 1×1 μm^2.

Fig. 10. Cross-sectional TEM images of samples grown at 830°C with a PH_3 flow rate of 2700 μmol/min and growth pressure of 300 Torr. (a) A sample grown for 12 min. Marker represents 50 nm. (b) High resolution image of the sample. Marker represents 5 nm. (c) High resolution image of a sample with a 40-nm thick layer. Marker represents 5 nm.

Table I. Growth parameters for GaP on Si substrates.

Sample	T_g (°C)	pressure (Torr)	PH_3 (μmol/min)	TEG (μmol/min)	V/III	time (min)
a	700	100	450	3.4	132	20
b	700	100	1350	3.4	396	20
c	700	300	450	3.4	132	20
d	700	300	1350	3.4	396	20
e	800	100	450	3.4	132	20
f	800	100	1350	3.4	396	20
g	800	300	450	3.4	132	20
h	800	300	1350	3.4	396	20
i	830	100	450	3.4	132	20
j	830	100	1350	3.4	396	20
k	830	300	450	3.4	132	20
l	830	300	1350	3.4	396	20
m	830	100	1350	14.0	192	20
n	830	100	2700	14.0	192	40
o	830	300	1350	14.0	192	40
p	830	300	2700	14.0	192	60
q	830	300	2700	14.0	192	20

Table II. Island density at 700 and 800°C.

pressure (Torr)	PH_3 flow rate (μmol/min)	island density at 700°C (cm^{-2})	island density at 800°C (cm^{-2})
100	450	3.0×10^7	1.9×10^8
100	1350	1.3×10^8	-
300	450	1.6×10^8	3.0×10^9
300	1350	3.0×10^8	3.3×10^9

Table III. Growth thickness of GaP layers.

Sample	T_g (°C)	pressure (Torr)	PH_3 (μmol/min)	thickness (nm)	rms (nm)
g	800	300	450	100	17
h	800	300	1350	75	11
j	830	100	1350	130	25
k	830	300	450	60	9.3
l	830	300	1350	25	2.6

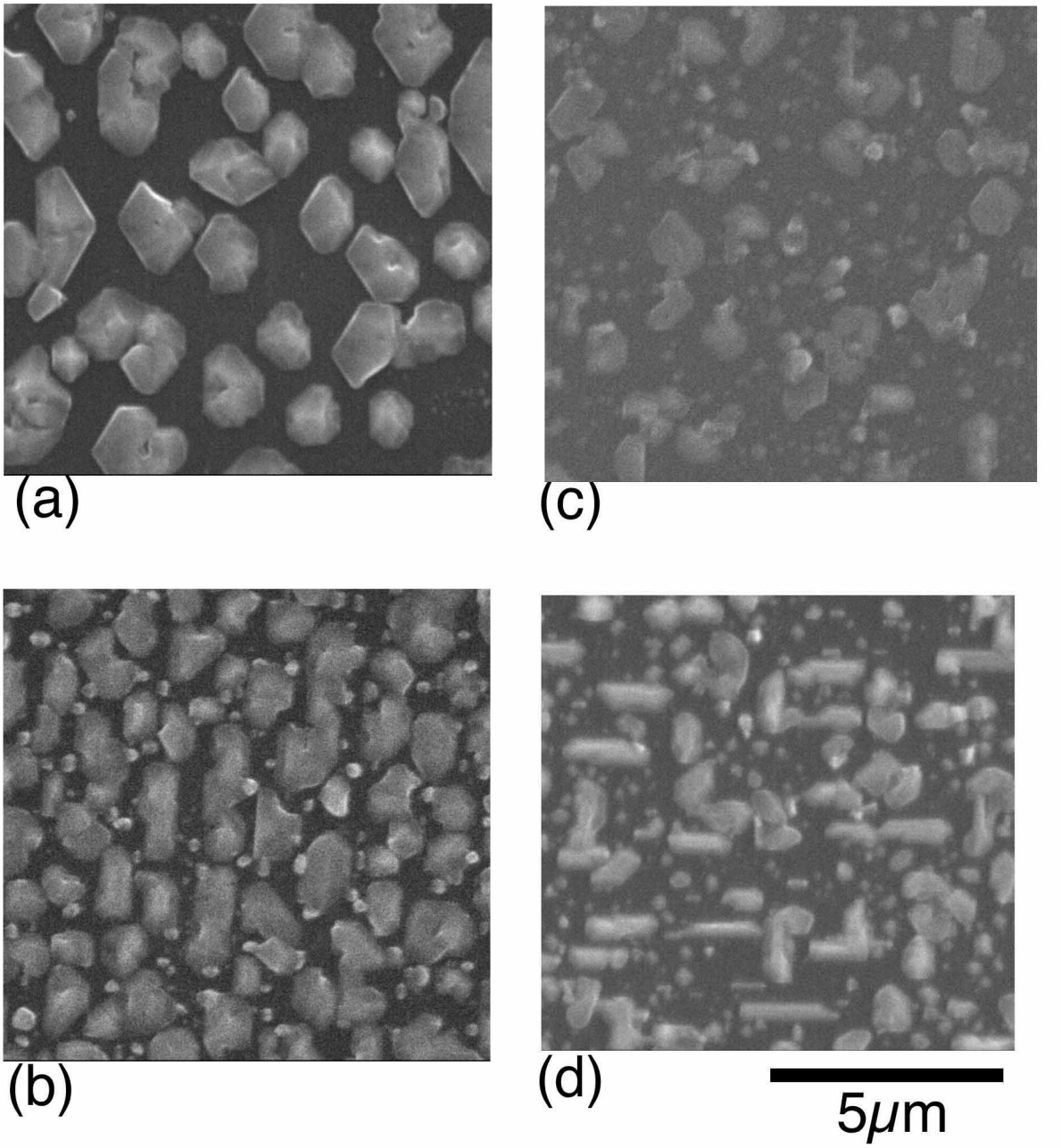


Fig. 1

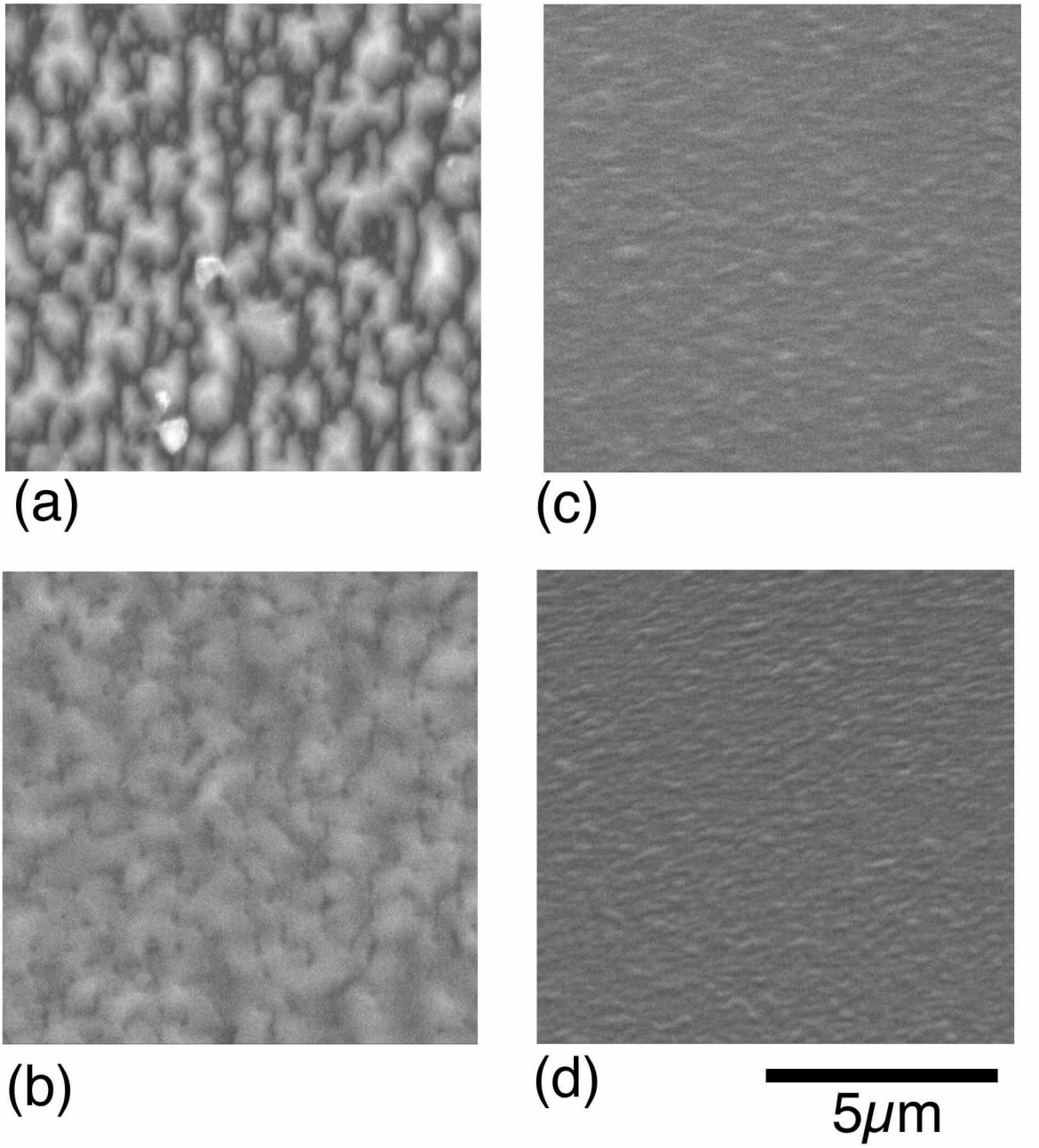
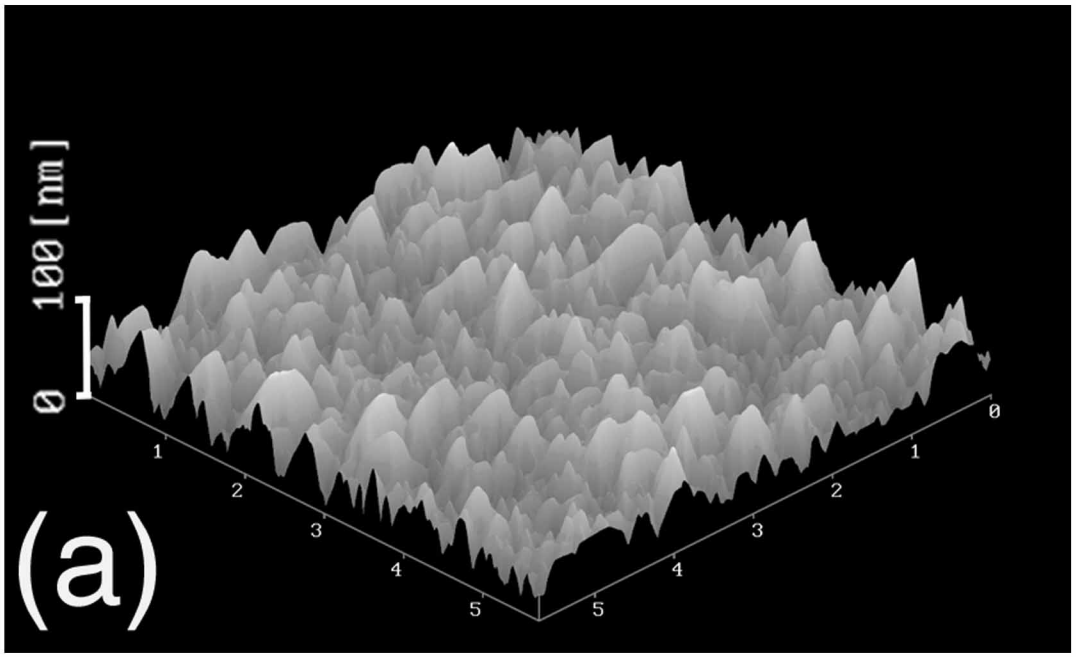
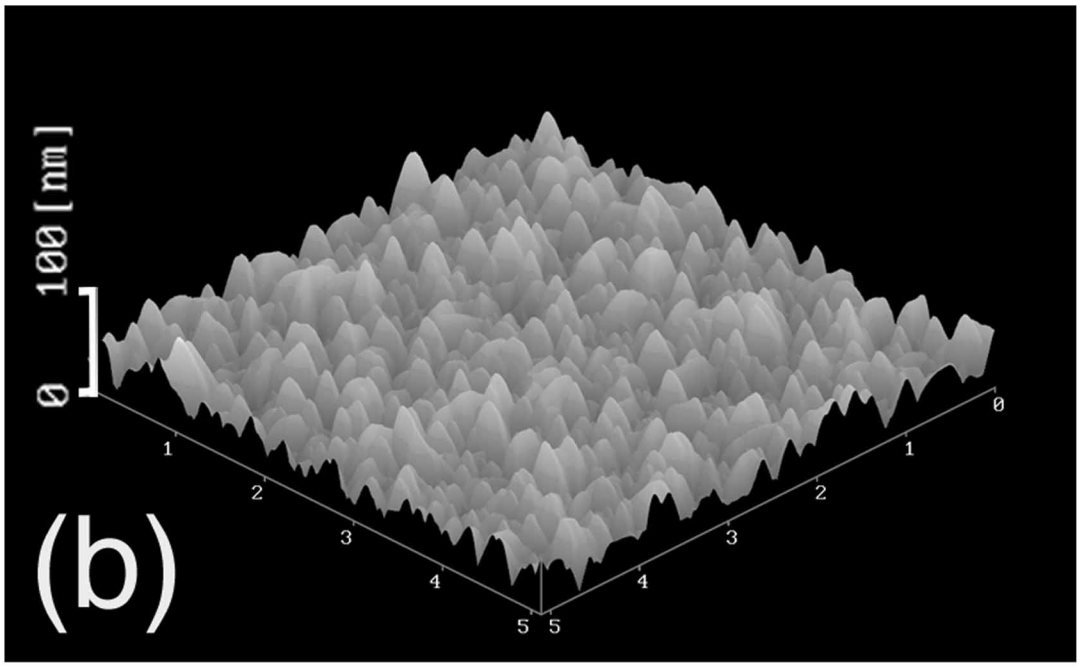


Fig.2





5μm

Fig.3

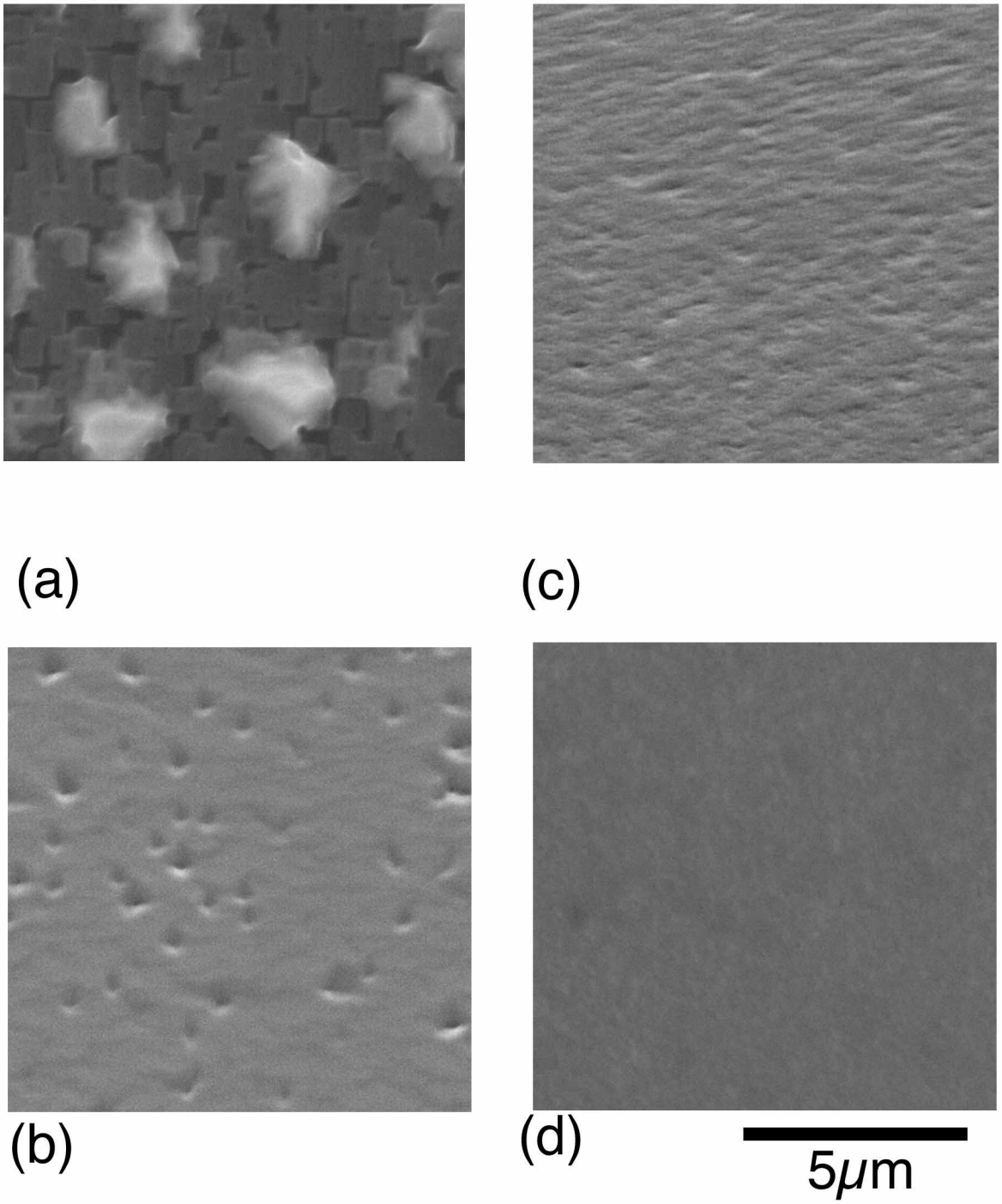


Fig.4

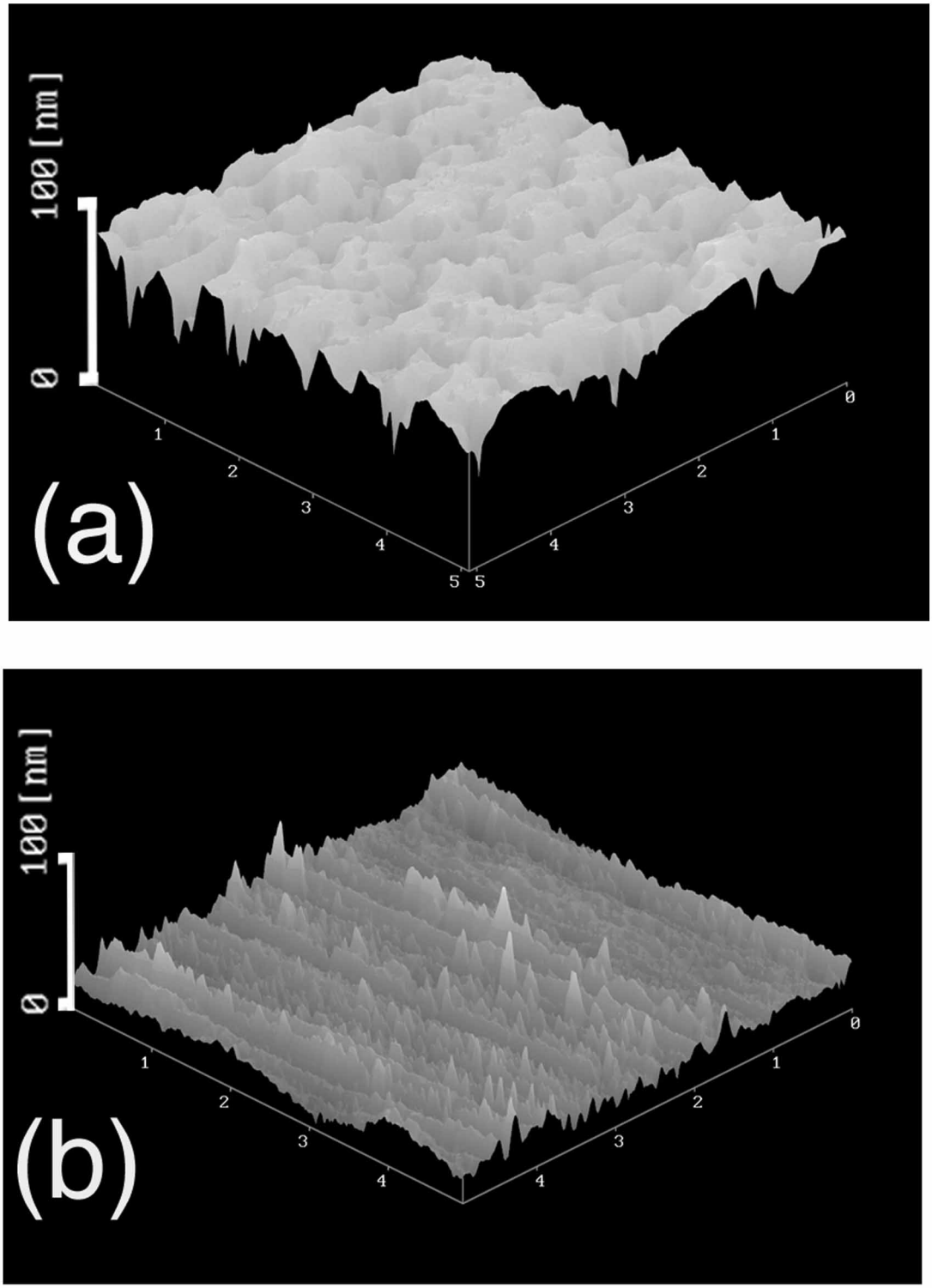


Fig.5

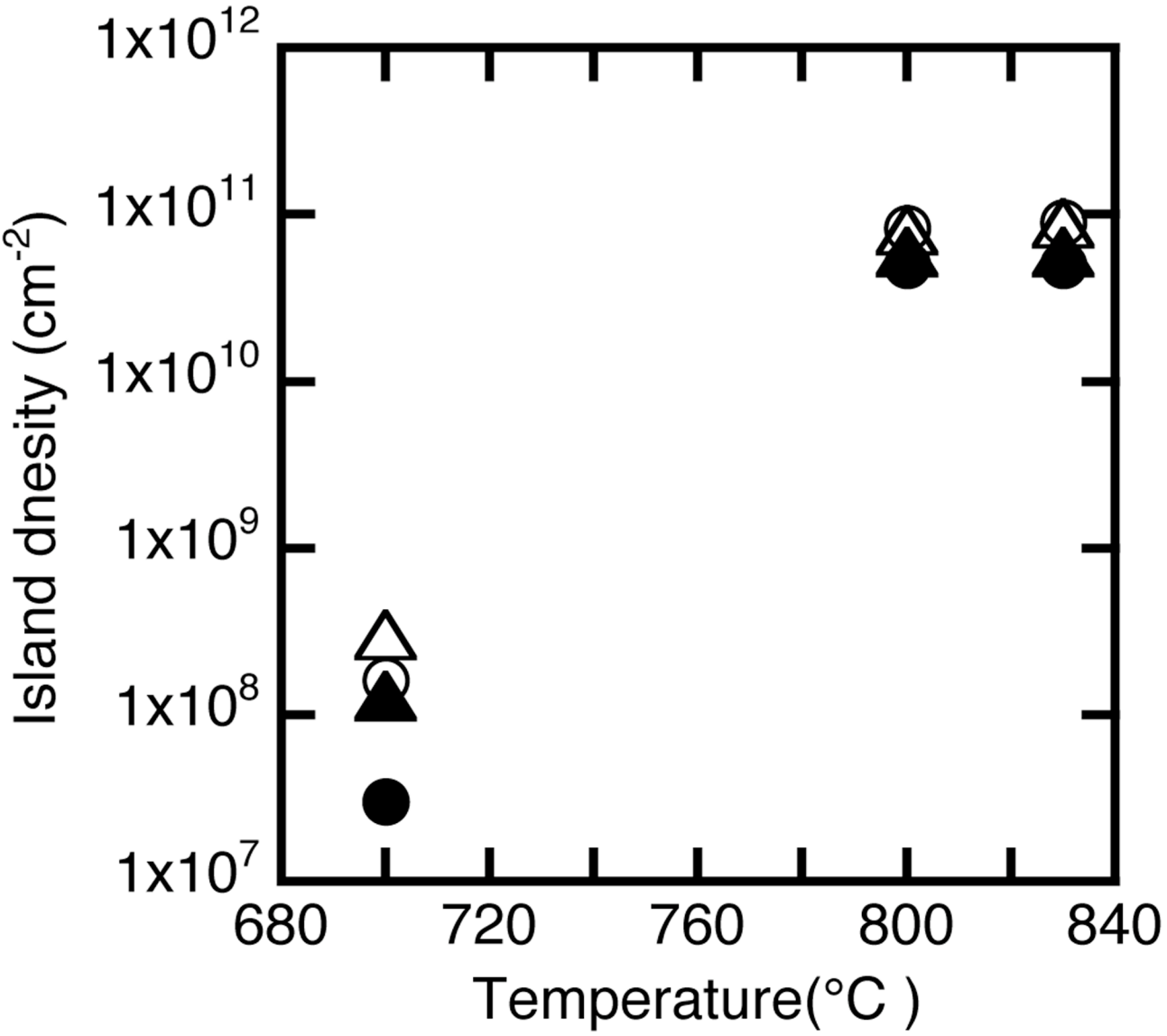
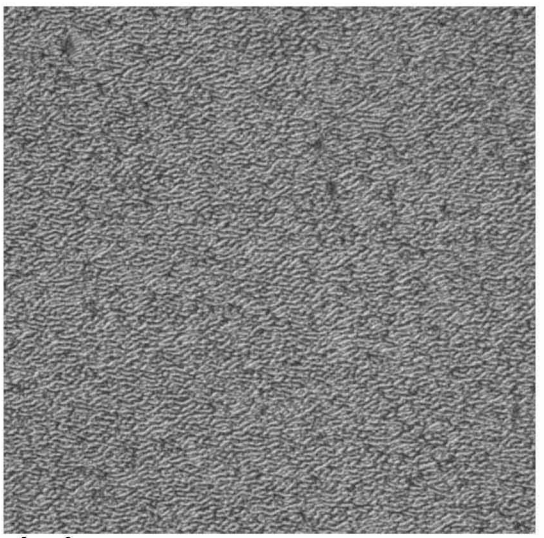
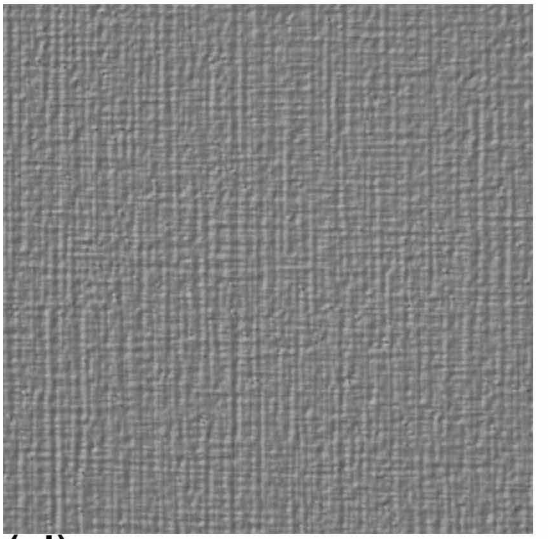

1x10^12
1x10^11
1x10^10
1x10^9
1x10^8
1x10^7
Island dnesity (cm^-2)
680
720
760
800
840
Temperature(°C)

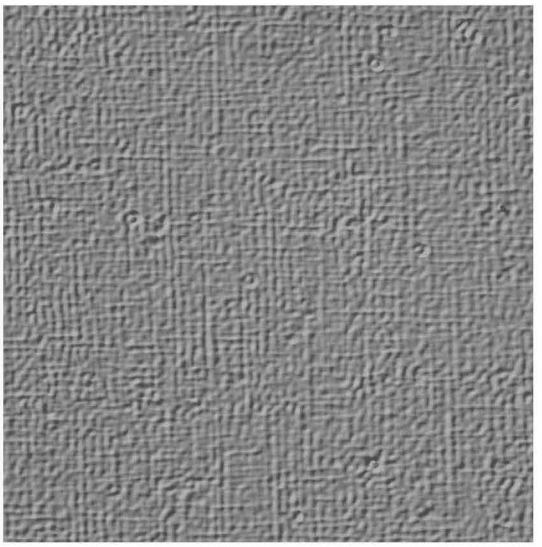
Fig. 6



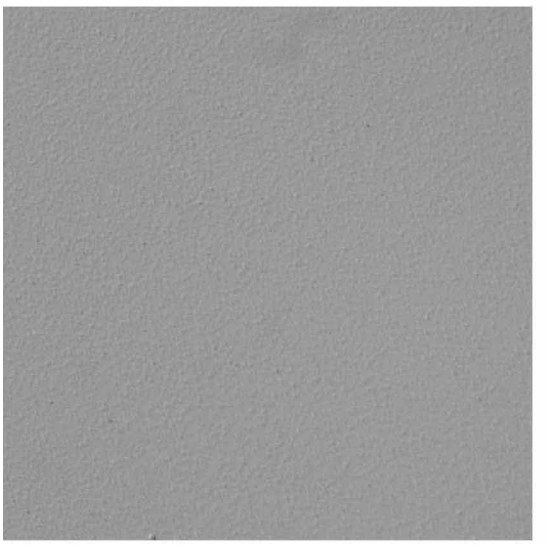
(a)



(d)

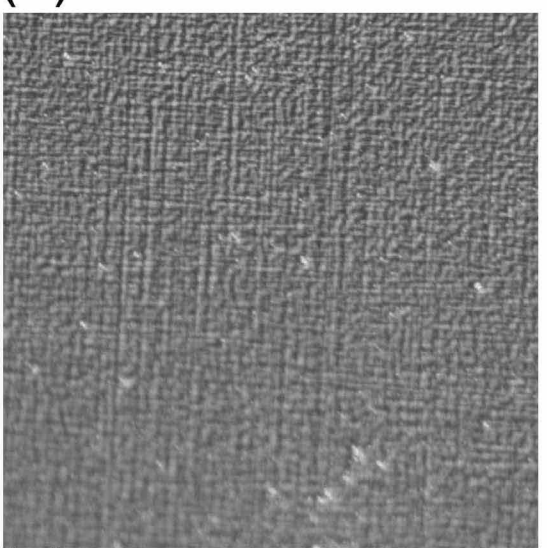


(b)



(e)

20μm



(c)

Fig.7

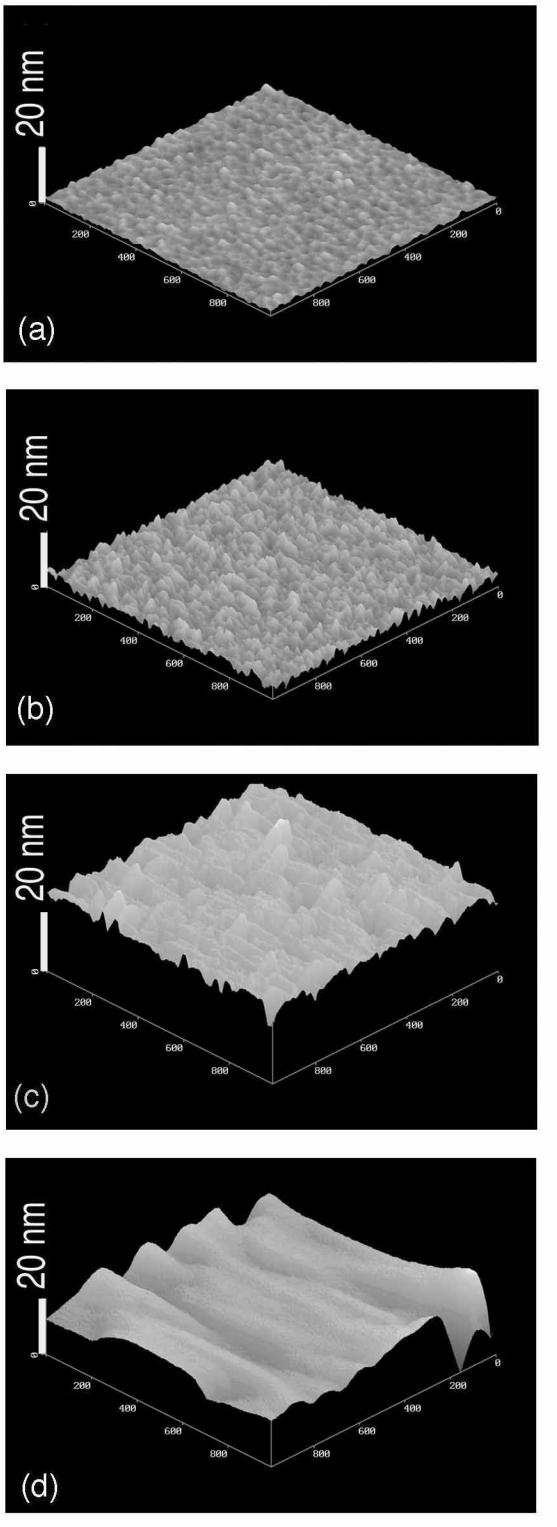
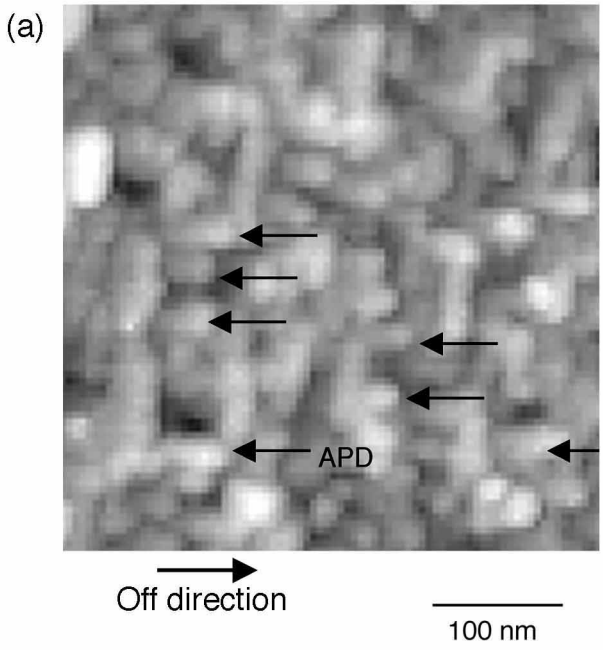
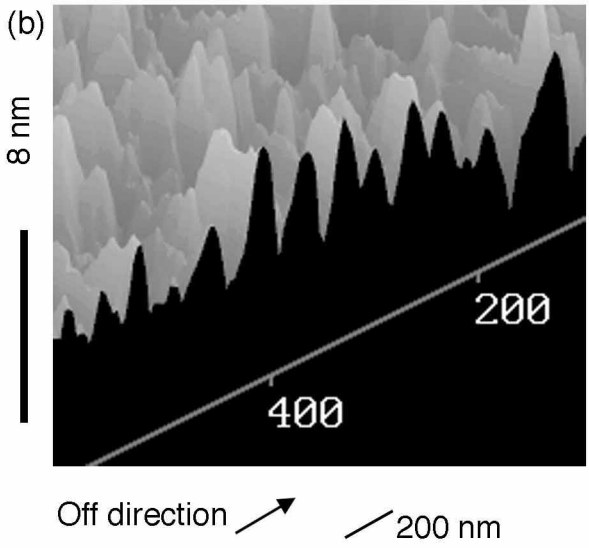


Fig. 8


(a)
APD
Off direction
100 nm


(b)
8 nm
200
400
Off direction
200 nm

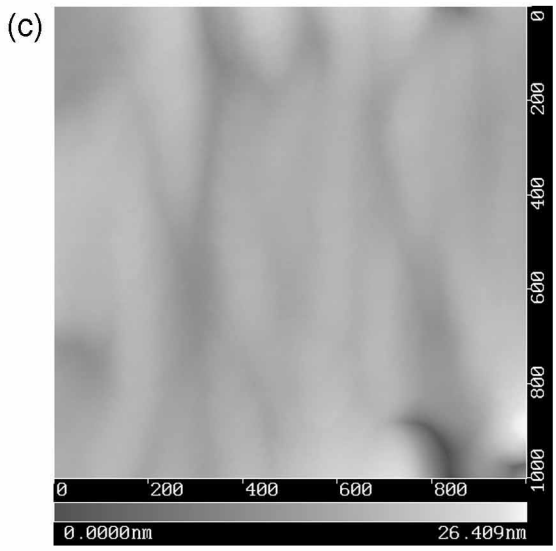

(c)
0
200
400
600
800
1000
0.0000nm
26.409nm

Fig. 9

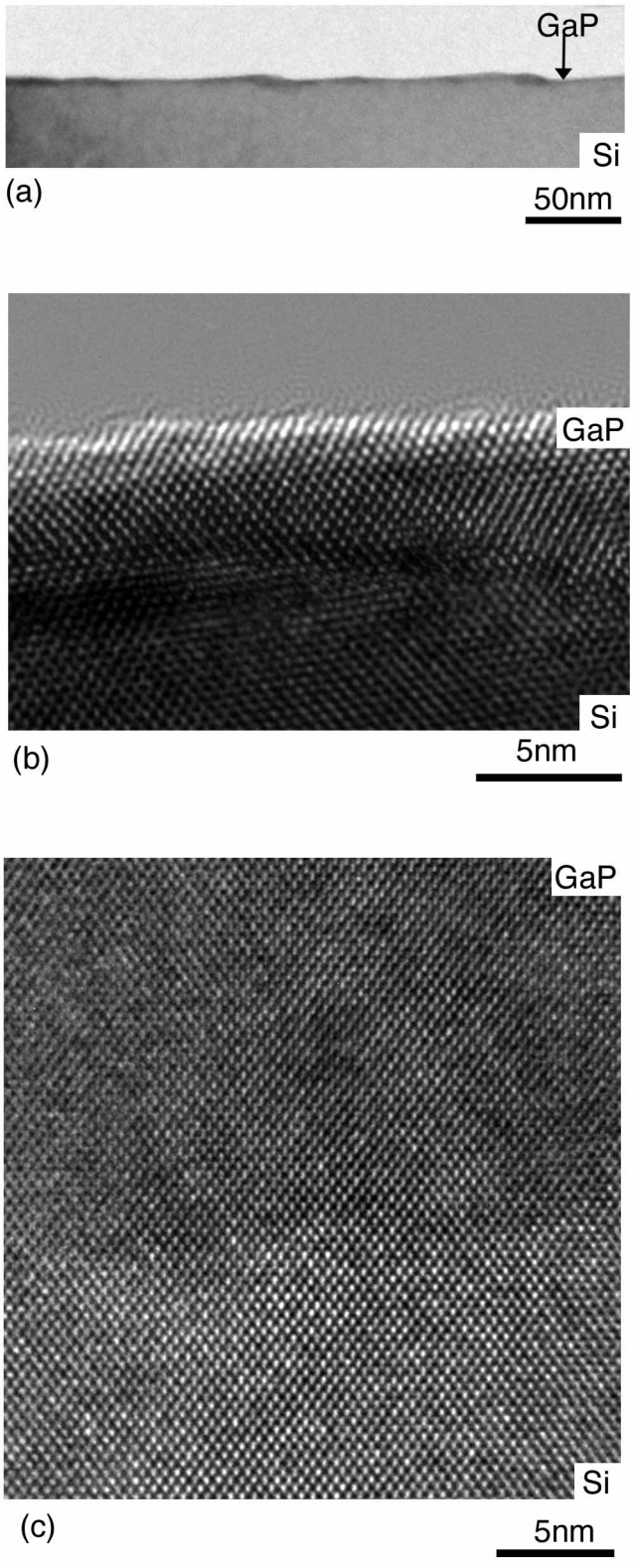


Fig.10