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Formation and preferred growth behavior of grooved seed silicon substrate for kerfless technology*

Jing-Yuan Yan(鄢靖源)[1,2], Yong-Wei Wang(王勇炜)[1,2], Yong-Ming Guo(郭勇明)[1,2], Wei Zhang(张伟)[2], Cong Wang(王聪)[2], Bao-Li An(安保礼)[1,†], and Dong-Fang Liu(刘东方)[2,‡]

[1] *College of Sciences, Shanghai University, Shanghai* 200444, *China*
[2] *Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai* 201210, *China*

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Kerfless technology is a promising alternative for reducing cost and providing flexible thin crystals in silicon-based semiconductors. In this work we propose a protruded seed substrate technology to prepare flexible monocrystalline Si thin film economically. Grooved seed substrate is fabricated by using SiN_x thin film as a mask for the wet-etching and thermal oxidation process. After the SiN_x layer on the wedged strip is removed by hot phosphoric acid, the pre-defined structured substrate is achieved with the top of the strip serving as the seed site where there is no oxide layer. And a preferred growth of epitaxial Si on the substrate is performed by introducing an intermittent feed method for silicon source gas. The technique in this paper obviously enhances the mechanical stability of the seed structure and the growth behavior on the seed sites, compared with our previous techniques, so this technique promises to be used in the industrial fabrication of flexible Si-based devices.

Keywords: kerfless, grooved seed substrate, preferred growth

PACS: 68.55.ag, 68.55.–a, 81.10.–h, 81.16.Rf **DOI:** 10.1088/1674-1056/28/6/066802

1. Introduction

Si thin or ultrathin crystals are crucial in applications such as flexible solar cells, silicon-on-insulator (SOI), flexible integrated circuit (IC) chips, insulated gate bipolar transistor (IGBT), *etc*.[1–8] In order to avoid kerf loss during Si wafer thinning process that has frustrated people for years, kerfless technology is eagerly demanded. On the one hand, kerfless technology can reduce about 30% of the total cost in slicing process in which a traditional Czochralski method is used;[9,10] on the other hand, thin/ultrathin and flexible silicon crystals are readily available by epitaxial growth and transfer approaches directly. Double layer porous silicon method, one of the kerfless techniques,[11,12] is capable of preparing kerfless flexible Si thin crystals with good properties. However, limited reuse times of the substrate and metal contaminants from electrochemical electrodes restrict its wide industrial applications.

In our team's previous research, the patterned rod arrays with wax acting as the filling mask provided protruded Si seeds by removing the oxide layer on the heads of the patterned rods, and the epi-Si film/wafer grown on them had texturized surface with the same periodicity as the original rod pattern. The uniformly structured hollows have been built between the epi-Si film and the substrate so that the epi-Si film could be transferred without sacrificing any layer, thereby making the substrate reusable.[13] Due to the difficulty in using wax to form uniform and flat thin films, only long rod arrays are applicable to fabricating the seeded substrates with wax used as filling mask. In order to enhance the mechanical stability of the seed structure and increase the reuse possibility of the structured substrate, short rods would be preferred. Later, efforts had been made to fabricate seeded substrates with shorter rod arrays by a joint resist mask method.[14] Thermal evaporation deposited aluminum film, spin-coated poly methyl methacrylate (PMMA) and photoresist were used to form the joint mask. Protruded seed substrate was achieved by removing the oxide layer selectively from the rod heads under the masking effect of the joint mask. However, multiple filling and etching process were involved in the joint mask method, and the processing is complicated and boring.

In this article, we demonstrate a simple and low-cost approach to preparing mechanically stable wedge-grooved seed substrates with SiN_x thin film serving as the mask layer for wet-etching and thermal oxidation without expensive inductive coupled plasma dry-etching process.[15,16] The vapor phase epitaxial growing process is implemented to produce epi-Si on this substrate by using gaseous $SiCl_4$ as a silicon source.[17] An intermittent silicon-source-feeding technique is used to control the preferred growth behavior on the seed sites and well-faceted growth is successfully performed. The endeavors shown in this work will promote the development of

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†Corresponding author. E-mail: blan@shu.edu.cn
‡Corresponding author. E-mail: liudf@sari.ac.cn

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kerfless technology for further industrial applications.

2. Experiment

2.1. Formation of grooved seed Si substrate

Figure 1 shows the process for the fabrication of the grooved seed Si substrate. A 4-inch (1 inch = 2.54 cm) diameter (100)-oriented Czochralski monocrystalline Si (Cz-Si) wafer coated with 80 nm SiN_x thin film by plasma-enhanced chemical vapor deposition (PECVD) was used as a mother substrate. The periodically patterned SiN_x strip array along the $\langle 110 \rangle$ direction was prepared by the traditional photolithography and reactive ion etching (RIE) on the substrate. Acetone was employed to remove the remaining photoresist. With the striped SiN_x film as a mask, V-grooved texturization on the substrate was performed by wet-etching in a solution of 40% KOH (potassium hydroxide, Greagent) and 20% IPA (isopropanol, Greagent) for 20 min at 80 °C. After the texturization, thermal oxidization was used to form an SiO_2 sheath layer on the wafer and V-grooves, typically, the oxidization duration was 12 h at 900 °C, and the thickness of oxide layer was 300 nm. Finally, the SiN_x masks were removed in boiling 85% H_3PO_4 solution for 20 min, thus the silicon inner layer was exposed on the top of the wedged strips, forming seeded sites for later selective growth of epi-Si.

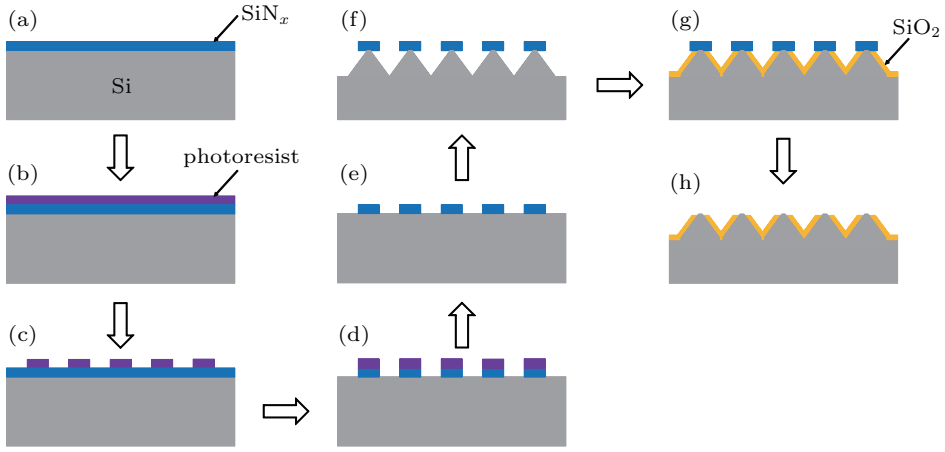


Fig. 1. Fabrication process of grooved seed Si substrate: (a) SiN_x deposition, (b) photoresist spin-coating, (c) photolithography, (d) RIE etching of SiN_x, (e) photoresist lift-off, (f) silicon wet etching, (g) oxidization, and (h) removal of the left SiN_x mask.

2.2. Vapor phase epitaxial growth of silicon

The growth of epi-Si was conducted in an induction heating system by using a vertically-placed and water-cooled quartz tube as a chamber,[18] and the substrate was directly placed on silicon-coated graphite susceptor. Before the epitaxial growth, the substrate was immersed in a dilute HF (1.5%) solution for 30 s and reduced under hydrogen atmosphere for 10 min at 1000 °C to get rid of the native oxide layers on the seeded sites. When the epi-growth was performed, the substrate was kept at 1200 °C under atmosphere pressure using $SiCl_4$ gas (Arkonic Gases & Chemicals Inc., 99.9999%) as the silicon source and H_2 (Airgas, 99.9999%) as the carrier gas.[19] In the uninterrupted growth mode, 2000-sccm H_2 and 24-sccm $SiCl_4$ were introduced into the chamber, and the growth duration was 30 min. In order to enhance the selectivity of the growth on the seeds, intermittent silicon-source feed mode was adopted. In the intermittent mode, the substrate was exposed in pure H_2 with a time interval ranging from 2 to 3 min after an epitaxial growth of 1 min–3 min. The total growth times were 30 min, 1 h, and 2 h respectively.

3. Results and discussion

The morphology of the obtained grooved seed Si substrate and energy dispersive spectrum (EDS) analysis are shown in Fig. 2. Figures 2(a) and 2(b) demonstrate that the wet-etching of the substrate has high self-discipline characteristics under the mask of SiN_x stripes, and the formed strips present wedge-like shapes. The angle at the bottom of V-grooves is 70.5°, similar to the one between adjacent Si {111} planes, indicating that only Si {111} plane remains during etching process,[20] and also that the areas with SiN_x masks are kept from alkaline etching, thus defining the shape and size of the grooved Si seed. In order to show up the seeded sites and prove the seed architecture, *i.e.*, silicon surface exposed only on the top of the wedged-strips, a diluted KOH solution is used to etch the prepared seed substrates. Figures 2(c) and 2(d) reveal that shallow depressions appear on the tops of the wedged-strips, indicating the etching has happened here by KOH solution, but other surface on the seed substrate is protected from visibly etching. This phenomenon made it clear that the silicon surface is exposed just on the tops of the wedged-strips and the other surface of the substrate is sheathed. The EDS spectra further prove the architecture of the seed substrate. As shown in Fig. 2(e), the SiN_x layer

stands on the top of the wedged-strip and a pure silicon surface is exhibited on the V-grooves after the KOH wet etching of the original silicon substrate under the mask of striped SiN_x film, but after the procedures of thermal oxidization and removal of the left SiN_x on the strip top, pure silicon surface is exposed on the strip top and the grooves are sheathed by oxide layers. As a result, the seeded substrates are well-built and ready to be used for the epi-Si growth.

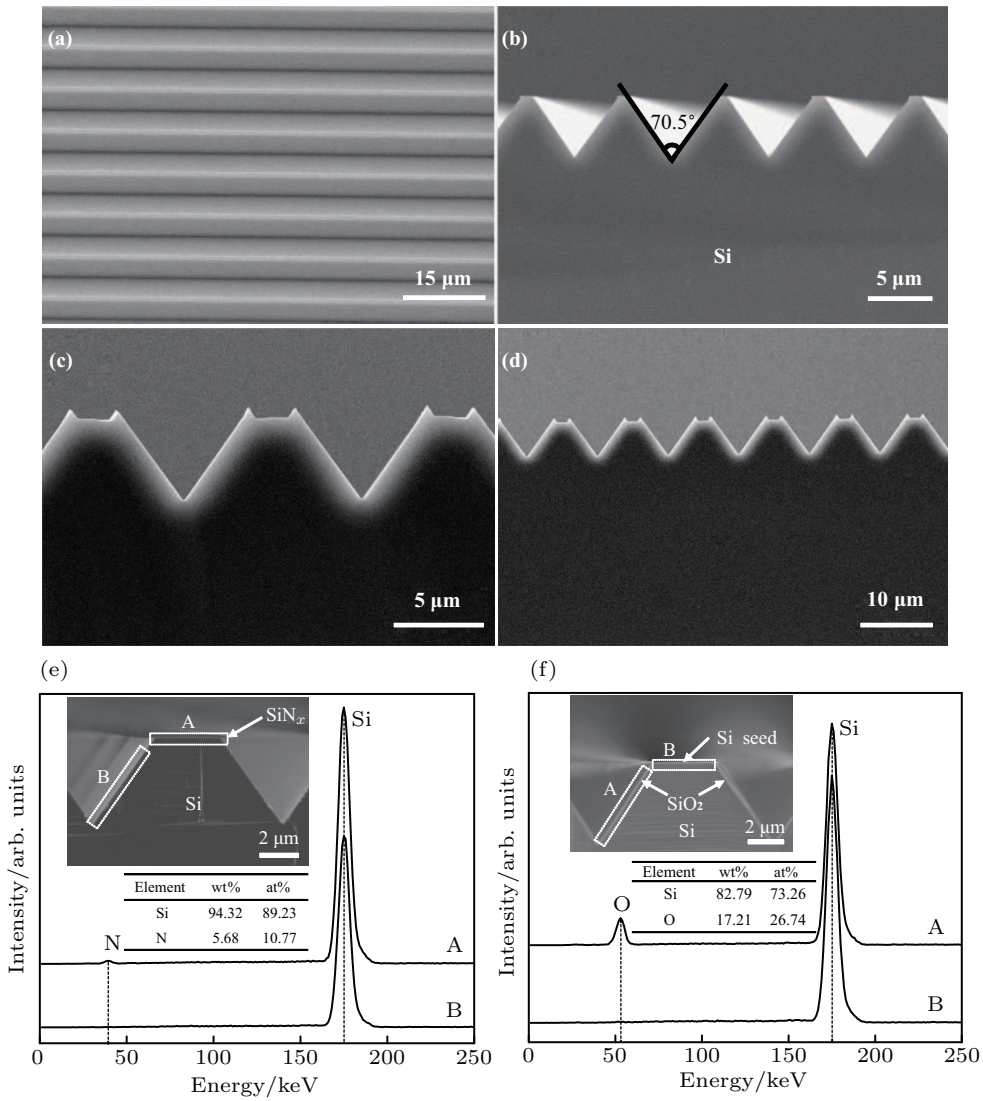


Fig. 2. SEM images of the grooved substrate, (a) bird view, and (b) cross-section; showing up images of seeded sites by diluted KOH etching, (c) zoom-in, and (d) zoom-out; cross-sectional SEM image and EDS spectrum of single wedged strip, (e) as-prepared by wet-etching under the mask of SiN_x, and (f) after thermal oxidization and removal of the left SiN_x mask layers.

Figure 3 illustrates the morphologies of epi-Si grown on the substrate. Epi-Si grown in the uninterrupted mode is shown in Fig. 3(a), it appears that the shape of the grown epi-Si is irregular, and although the epitaxial growth is preferred on the seeded sites, a fast lateral overgrowth also occurs downward along the slopes of the V-grooves. It is inferred that the fast downward lateral growth results from the high supersaturation of silicon tetrachloride that migrates from the V-groove surface to the interface between the grown silicon and the oxide layer, and the irregular shape of the grown silicon rises from the reverse etch reaction of by-product chlorides on the silicon surface because the concentration of by-product chlorides in the chamber is accumulated with the growth duration increasing. In order to achieve well-faceted surface and enhance the anisotropic growth over the groove, the intermittent source gas feeding method is adopted.[21–23] The morphology evolutions of the epi-Si with the silicon source feed mode are demonstrated in Figs. 3(a)–3(d). Obviously, the grown epi-Si becomes better faceted and larger over the groove with the faster repetition rate of $SiCl_4$ on-and-off feeding, as well with shorter on-and-off intervals, from Figs. 3(a)–3(d). Additionally, the size of grown Si does not vary much in Fig. 3(b) nor in Fig. 3(c) compared with that in Fig. 3(a) although the total amount of $SiCl_4$ feeding decreases to 1/2 and 1/3 of that in Fig. 3(a) for the whole growth duration. In other words, the intermittent feed mode increases the growth rate of the epi-Si. Since the carrier gas, H_2 with a light molecular weight, has a rather weak carrying capability under the atmosphere pressure,

the concentration of chloride byproduct, such as HCl, from the reduction reaction between $SiCl_4$ and H_2, would accumulate around the substrate holder zone with the growth duration increasing. It is understandable that the intermittent feed mode would restrain the byproduct accumulation. Thus the conversion rate of $SiCl_4$ into Si is promoted as can be seen from Figs. 3(a)–3(c), and less reverse etch reaction on the grown Si results in better faceted surfaces.

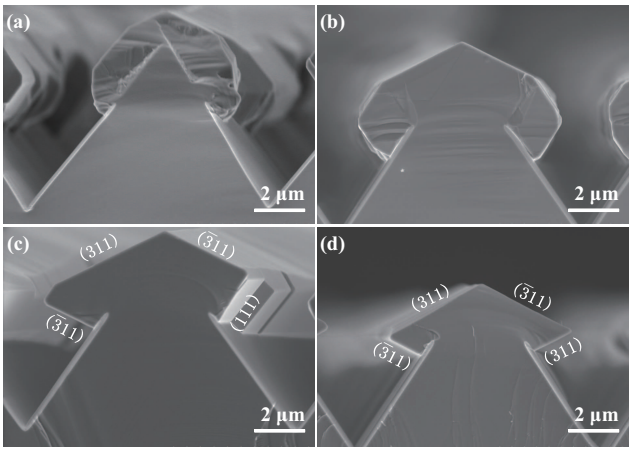


Fig. 3. Cross-sectional SEM images of the epi-Si under different $SiCl_4$ feeding modes: (a) uninterrupted 24-sccm $SiCl_4$ feeding for 30 min; (b) intermittent 24-sccm $SiCl_4$ feeding for 30 min (3-min turn-on/3-min turn-off); (c) intermittent 24-sccm $SiCl_4$ feeding for 30-min (1-min on followed by 2-min off); (d) intermittent 12-sccm $SiCl_4$ feeding for 60 min (1-min on followed by 2-min off).

According to the intersection angles between faceted surfaces of the grown Si and the grooves, the surface planes of the grown Si are indexed in Figs. 3(c) and 3(d). It is revealed that the front side surfaces facing the gas flow are indexed to $\{311\}$ both in Fig. 3(c) and in Fig. 3(d), but for the back side surfaces against the gas flow, one is indexed to $\{111\}$, the other is indexed to $\{311\}$ in Fig. 3(c); contrastively, both back surfaces are symmetrically indexed to $\{311\}$ in Fig. 3(d). Si crystal belongs to the cubic crystal system with the two-fold symmetry along the $\langle 110\rangle$ direction. Bravais–Friedel law states that high index crystal planes with small interplanar spacings grow faster than the low index ones, and thus the high index planes are not seen in the final shape of the crystal.[24] Therefore, from the point of crystallographic growth habit, the shape of the crystal is determined by the relative growth rate at various crystal planes. Si crystal belongs to the cubic crystal system with the two-fold symmetry along the $\langle 110\rangle$ direction. In the case of $\langle 110\rangle$ crystallographic direction family in the cubic crystal system, the lowest index plane belongs to $\{111\}$ and the second lowest one is $\{311\}$. Therefore, considering both the crystallographic growth habit and the symmetry, the surface planes of the grown Si bars along the $\langle 110\rangle$ direction are surely adjacent $\{111\}$, $\{311\}$ planes, or parallel ones. Undoubtedly, the situation in Figs. 3(c) and 3(d) confirm the above theoretical analysis. Owing to the higher supersaturation of reactants on the surface facing the gas flow, the front surfaces are energetically apt to be $\{311\}$ planes both in Fig. 3(c) and in Fig. 3(d). On account of the shelter effect from the grown Si bars, less reactants can reach the back surfaces of the grown bars, and lower supersaturation of reactants on the back surface against the gas flow should energetically result in $\{111\}$ back planes both in Fig. 3(c) and in Fig. 3(d) because $\{111\}$ planes have lower surface-energy state than $\{311\}$ planes. It is thought that the feed of 12-sccm $SiCl_4$ in Fig. 3(d) is too small to provide enough reactants to form lower-energy state $\{111\}$ planes on the back of the grown bars, thus two higher-energy state $\{311\}$ planes are left behind there. Owing to the non-uniformity of the gas flow distribution in the chamber, even though the feed amount of $SiCl_4$ in Fig. 3(c) is double that in Fig. 3(d), one of the back-surface planes belongs to $\{111\}$, the other still belongs to $\{311\}$.

In order to obtain a faster growth rate and well-faceted surfaces of the grown Si bars, the growth conditions in Fig. 3(c) are used as the optimized ones, and 1-μm top width of the seed stripes is chosen for narrower necks that connect the grown Si bars with the mother substrate. The typical facet profile of the grown Si bars is displayed in Fig. 4, revealing that the surface facets are step-like, and all of them are indexed to $\{111\}$ and $\{311\}$ planes, but the combination of $\{111\}$ and $\{311\}$ planes is random for each individual grown bar since the reactant flow is hard to be uniformly distributed across the substrate. Anyway, the facet profile in Fig. 4 clearly verifies the dominance of the crystallographic symmetry and the Bravais–Friedel law of the silicon seed growth.

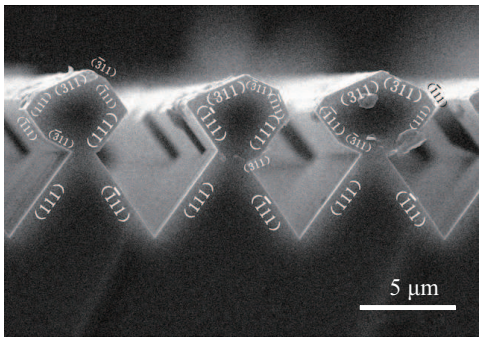


Fig. 4. Typical facet profile of grown epi-Si on grooved seed Si substrate.

From the point of the mass-transport in the course of epi-Si growth, the models of gas flow around the substrate are proposed in Fig. 5 to further clarify the growth mechanism on the seeded substrate. As shown in Fig. 5(a), at the initial stage of the epi-growth, there are two kinds of gas flows on the surface of the substrate, *i.e.*, flow 1 and flow 2. The flow 1 goes straight down to the substrate while a large portion of the flow 1 is reflected by the slopes of the V grooves and turns into the turbulent flow 2, then the flow 2 is trapped and enveloped by the V grooves and the flow 1. Consequently, at the initial stage, two parts of silicon reactant are gathered up at the seeded sites, *i.e.*, one is directly anchored from the flow 1 that

faces the seeded areas; the other diffuses from the flow 2 along the slopes of the grooves. Thus the supersaturation of the silicon reactant is quite high and the nucleation and growth-up of silicon quickly happen on the seeds at the early stage when the $SiCl_4$ gas is just introduced into the chamber. Once the epi-Si grows up to a size larger than the width of the seeded sites, the epi-Si will shelter the V-grooves from the flow 1, accordingly, as shown in Fig. 5(b), the curved flow 3 under the epi-Si and the parallel flow 4 at the opening of the groove come into being, and as a result, the trapped gas in the grooves turns harder to escape out. Therefore, it could be inferred that if the feed amount of $SiCl_4$ is fairly large, much of the byproduct chloride will be trapped in the grooves, and then diffuse and accumulate around the grown epi-Si, the growth rate of the epi-Si will be inhibited by the severe reverse etch reaction,

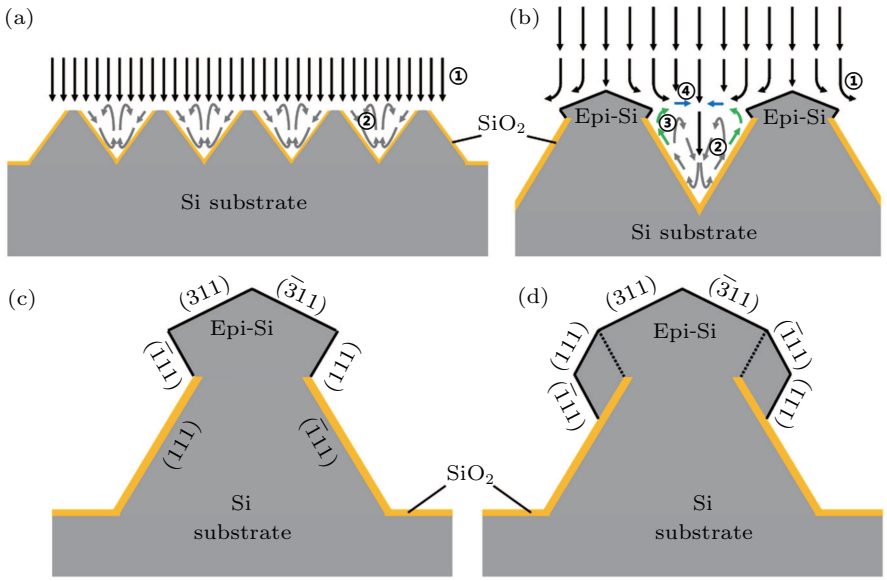


Fig. 5. Schematic diagram of (a) gas flow on seed area and V-grooves, (b) gas flow on epi-Si and V-shaped grooves, (c) morphology of epi-Si under equilibrium growth without lateral overgrowth on oxide layers, and (d) morphology of epi-Si under equilibrium growth with lateral overgrowth.

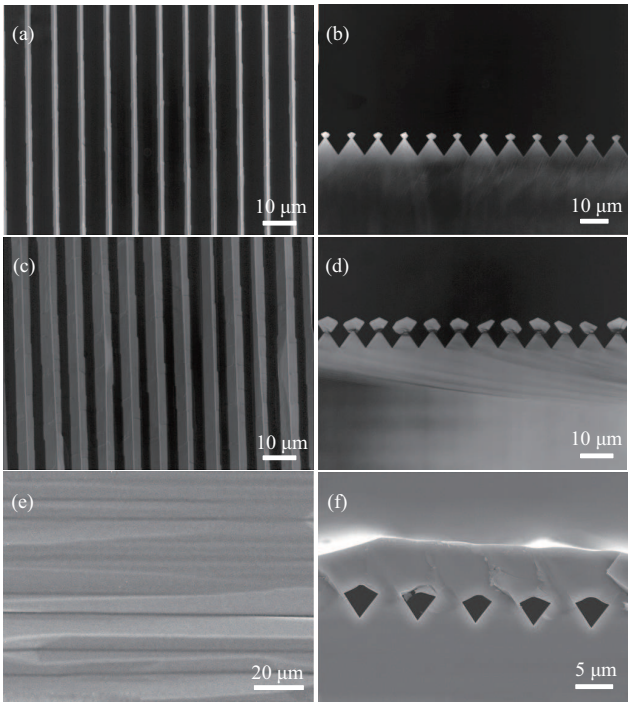


Fig. 6. Panorama of initial epi-Si for hollow-spaced continuous Si film. (a) Bird-view SEM image of epi-Si grown for 30 min, (b) cross-sectional SEM image of epi-Si grown for 30 min, (c) bird-view SEM image of epi-Si grown for 1 h, (d) cross-sectional SEM image of epi-Si grown for 1 h, (e) bird-view SEM image of epi-Si grown for 2 h. and (f) cross-sectional SEM image of epi-Si grown for 2 h.

and much lateral overgrowth will happen along the slopes due to the high degree of supersaturation at the interface between the grown Si and the oxide layers (as shown in Figs. 3(a) and 5(d), and it was very necessary that intermittent $SiCl_4$ feed mode is used to facilitate the trapped gas off the grooves. And the intermittent feed mode can help the epi-Si grow nearly under the equilibrium state, thereby well-faceted surfaces are formed (as shown in Figs. 3(c) and 3(d)). Figures 5(c) and 5(d) show the schematic facet profile of the grown Si bars under perfect equilibrium growth state, without and with lateral overgrowth along the oxide layers, respectively, but these phenomena hardly happen in actual experiments (the profile in Fig. 4 is common in experiments).

Using the intermittent feed mode in Fig. 3(c) as an optimized mode, figure 6 shows the panorama of prepared epi-Si from just shooting out on the seed sites, subsequently growing larger and over the grooves, eventually forming continuous film with hollows spacing the substrate. Evidently, the growth of Si along the seeded stripe is uniform, although slightly terraced. And the readily formed hollows between the grown film and the substrate are shaped into a tetragon usually with two-fold symmetry, which is determined by the faceted growth habit and the preferred growth behavior. And the hollows build

weak mechanical connection of grown films with the mother substrate, and will make the aimed kerfless technology practical. The surface of the grown film is randomly texturized with grooved depressions, which also results from the faceted epi-growth and the non-uniformity of the reactant flows. The epi-growth panorama on the seeded substrate verifies the principle for kerfless silicon wafers by the vapor phase epi-growth method through using V-grooved seed substrates. By the way, in the traditional Siemens method to produce the crystalline Si, the $SiHCl_3$ is most used as a silicon source because of the higher conversion rate, the faster growth rate,[25] and the lower growth temperature than those of $SiCl_4$, if the $SiHCl_3$ is used in our experiments, better epi-growth and thicker films or wafers can be expected.

4. Conclusions

We exhibit a technique to fabricate grooved seed silicon substrates with well mechanical stability by using SiN_x film as a mask for the alkaline wet etching and thermal oxidization process, and by using the oxide layer as a mask for the selective removal of SiN_x film on the tops of the wedged strips to form seeded sites. This technique is compatible with the traditional silicon semiconductor processing technology, so it promises to possess industrial applications. The preferred epi-growth on the seeded substrates is dominated by the symmetry along the $\langle 110 \rangle$ crystallographic direction and the crystallographic facet habit. The proposed reactant gas flow model further clarifies the necessity of intermittent silicon source feed mode for well-faceted and controlled anisotropic epi-growth of silicon on the seeded sites. The success of growing continuous silicon films with readily-formed hollows spacing the grown films from the seeded substrates shows that our substrate promises to be applied to the kerfless technology for flexible silicon crystals or normal wafers.

References

[1] Bahabry R R, Kutbee A T, Khan S M, Sepulveda A C, Wicaksono I, Nour M, Wehbe N, Almislem A S, Ghoneim M T, Sevilla G A T, Syed A, Shaikh S F and Hussain M M 2018 *Adv. Energy Mater.* **8** 1702221

[2] Chang Y, Wei X, Zhu L, Su X, Gao N and Dong Y 2018 *Nucl. Instrum. Methods Phys. Res.* **426** 1

[3] Navaraj W T, Gupta S, Lorenzelli L and Dahiya R 2018 *Adv. Electron. Mater.* **4** 1700277

[4] Wang S, Xu J, Wang W, Wang G J N, Rastak R, Molina-Lopez F, Chung J W, Niu S, Feig V R, Lopez J, Lei T, Kwon S K, Kim Y, Foudeh A M, Ehrlich A, Gasperini A, Yun Y, Murmann B, Tok J B H and Bao Z 2018 *Nature* **555** 83

[5] Kano S, Tada Y, Matsuda S and Fujii M 2018 *Acs Appl. Mater. & Interfaces* **10** 20672

[6] Sun G D, Dong L X, Xue Z Y, Chen D, Guo Q L and Mu Z Q 2015 *Chin. Phys. B* **24** 036801

[7] Tan J, Zhu Y J, Lu S J, Tian X L, Teng Y, Yang F, Zhang G Y and Shen Q X 2016 *Acta Phys. Sin.* **65** 158501 (in Chinese)

[8] Shen S S, He C H and Li Y H 2018 *Acta Phys. Sin.* **67** 20181095 (in Chinese)

[9] Stockmeier L, Kranert C, Raming G, Miller A, Reimann C, Rudolph P and Friedrich J 2018 *J. Cryst. Growth* **491** 57

[10] Ge M, Bi W, Ge P and Gao Y 2018 *Int. J. Adv. Manuf. Technol.* **98** 3269

[11] Lee H S, Suk J, Kim H, Kim J, Song J, Jeong D S, Park J K, Kim W M, Lee D K, Choi K J, Ju B K, Lee T S and Kim I 2018 *Sci. Rep.* **8** 3504

[12] Gemmel C, Hensen J, Kajari-Schroder S and Brendel R 2017 *IEEEE J. Photovol.* **7** 430

[13] Zeng H, Zhang W, Li J, Wang C, Yang H, Chen Y, Chen X and Liu D 2017 *AIP Adv.* **7** 055307

[14] Li J Z, Zhang W, Yan J Y, Wang C, Chen H F, Chen X Y and Liu D F 2018 *Chin. Phys. B* **27** 086802

[15] Yamada K, Yamada M, Maki H and Itoh K M 2018 *Nanotechnology* **29** 28LT01

[16] Narasimha Rao A V, Swarnalatha V and Pal P 2017 *Micro Nano Syst. Lett.* **5** 23 (9 pp.)

[17] Cheng C, Zhang C, Jiang J, Ma E, Bai J and Wang J 2018 *J. Spectrosc.* 2329189

[18] Surovovs K, Plate M and Virbulis J 2017 *Magnetohydrodynamics* **53** 715

[19] Sukkaew P, Danielsson O and Ojamae L 2018 *J. Phys. Chem. A* **122** 2503

[20] Chen Q S, Liu Y P, Chen W, Zhao Y, Wu J T, Wang Y and Du X L 2018 *Acta Phys. Sin.* **67** 20181275 (in Chinese)

[21] Nieminen M, Sajavaara T, Rauhala E, Putkonen M and Niinisto L 2001 *J. Mater. Chem.* **11** 2340

[22] Tokairin M, Fujiwara K, Kutsukake K, Kodama H, Usami N and Nakajima K 2010 *J. Cryst. Growth* **312** 3670

[23] Shtertser A A, Ulianitsky V Y, Batraev I S and Rybin D K 2018 *Tech. Phys. Lett.* **44** 395

[24] Donnay J D H and Harker D 1937 *Am. Mineral.* **22** 446 ISSN: 0003-004X

[25] Watanabe T, Yamada A, Saito A, Sakurai A and Habuka H 2017 *Mater. Sci. Semicond. Process.* **72** 134