Spatially selective single-grain silicon films induced by hydrogen plasma seeding

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The enhancement of a hydrogen plasma treatment on the solid-phase crystallization of hydrogenated amorphous silicon has been applied to form single crystalline silicon islands at designed locations. Holes with diameters from 0.4 to 1.8 μm were opened in silicon nitride, and then amorphous silicon films within the holes were exposed to a hydrogen plasma to create microcrystalline seeds. After furnace annealing, the relationship between the size of holes and number of grains in the holes has been investigated. It is found that a single nucleus cannot be induced until the diameter of holes decreases below 0.6 μm. Further annealing enlarges the grain size by lateral growth but does not increase the number of grains in the hole. © *2002 American Vacuum Society.*
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I. INTRODUCTION

Polysilicon films crystallized from amorphous silicon have attracted much attention and are investigated for being active layers in thin film transistors (TFTs), which are used to drive and switch the image pixels in active matrix liquid crystal displays,[1] and are also used in silicon-on-insulator technologies for three-dimensional integrated devices.[2] The electrical characteristics of polysilicon TFTs are strongly dependent on the polysilicon microstructure. Grain boundaries are scattering centers which decrease carrier mobility and also serve as midgap states to increase leakage current. To improve the performance of polysilicon TFTs, one would want to locate the TFTs within a single grain of the polysilicon between grain boundaries. Therefore, it is of much interest to control the location of single-grain regions.[3,4] In this article, we demonstrate a method to produce such grains based on the plasma-induced crystallization of silicon in very small holes.

The solid-phase crystallization (SPC) of amorphous silicon involves two steps, i.e., nucleation and growth. A single nucleus induced during the nucleation stage is the prerequisite of the formation of the single-grain island. To date, several methods have been demonstrated to enhance the nucleation of *a*-Si:H SPC, such as metal-induced SPC,[5] germanium-induced SPC,[6] ion-beam-induced SPC,[7] and plasma-induced SPC.[8,9] Although the original motivation of these methods was to reduce the thermal budget of SPC, they can be used to induce the single nucleus and increase grain size by lateral growth from seeding sites into the amorphous matrix. The formation of single-grain islands at designed locations has been reported by methods of silicon ion implantation[3] and metal imprint.[4] For the method of silicon ion implantation, two ion implantation steps are required. The nickel-imprint technology[4] needs a silicon template with nickel coating, which may be not appropriate for the large-area electronics. Single-grain silicon islands by plasma seeding has not been reported, although plasma-induced SPC has the attributes of possible minimum metal contamination, minimum radiation damage, and most scalability for manufacturing.

II. EXPERIMENT

It has been reported that a hydrogen plasma treatment (HPT) on amorphous silicon films at room temperature enhances the rate of solid-phase crystallization, and thus can reduce the crystallization time from 20 to 4 h at 600 °C.[9] The hydrogen plasma actively abstracts hydrogen from the amorphous silicon and creates seed nuclei in the top 30 nm of the film. This process can be spatially masked by covering the surface of *a*-Si:H with the silicon nitride film and then opening holes in the nitride where the hydrogen seeding process will be derived. There is no accelerated crystallization under the nitride films.

Figure 1 shows the experimental steps for the formation of single-grain islands. First, 100 nm thick undoped amorphous silicon was deposited on an oxidized silicon substrate at 150 °C with rf power of 18 mW/cm^2 by plasma-enhanced chemical vapor deposition (PECVD). During deposition, the flow rate of silane is 50 sccm and pressure stabilizes at 500 mTorr. The hydrogen concentration is ~17% (atomic) in the amorphous silicon. Silicon nitride with 200 nm thickness was then deposited by PECVD at 200 °C, which has been demonstrated not to reduce the hydrogen concentration in *a*-Si:H (Ref. 10) and has little effect on the hydrogen–

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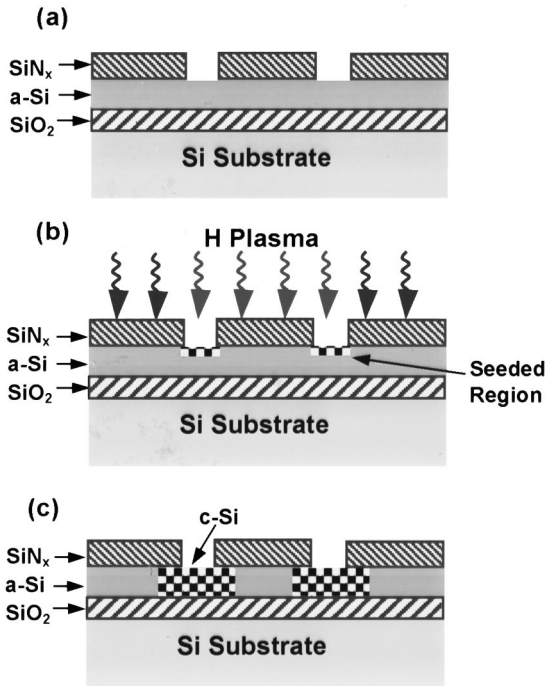

FIG. 1. Experimental processes of selective polysilicon formation induced by masked hydrogen plasma and subsequent crystallization: (a) formation of seeding window in the deposited SiN_x, (b) nucleation by hydrogen plasma, and (c) lateral growth /crystallization during subsequent anneal.

plasma enhancement of SPC. Holes with diameters from 0.4 to 1.8 μm were opened in the silicon nitride film by electron-beam lithography and dry etching. The samples were then exposed to a hydrogen plasma in a parallel-plate reactive ion etcher at the optimum condition[9] with a rf power of 0.8 W/cm^2, hydrogen flow rate of 50 sccm, and pressure of 50 mTorr. The low pressure and high power are designed to give a high hydrogen ion energy. Finally, the nitride films were removed by wet etching and the samples were annealed at 600 °C in nitrogen. The crystallinity of the silicon film was monitored by ultraviolet reflectance (λ=276 nm). Samples for transmission electron microscope (TEM) observation were prepared by a lift-off process. Silicon island films, first pattered into 1 × 1 mm^2 islands, were lifted off from the oxidized silicon substrate by a HF solution. The peeled-off films were placed onto copper grids for TEM observation. Grain size is measured by the formula $d=\sqrt{4A/\pi}$, where d is the grain size and A is the grain area.

III. RESULTS AND DISCUSSION

TEM observations on polysilicon films without HPT are shown in Fig. 2. Grains were located randomly on the film with the size of 0.3–0.8 μm. Figure 3 shows the selective crystallization and lateral growth through scanning electron microscope (SEM) and TEM for samples with large seeding holes (~3 μm) which were annealed for: (a) and (b) 6 h and (c) and (d) 10 h. The dark areas in Figs. 3(a) and 3(c) are fully crystallized polysilicon, but the white areas are still amorphous, which has been confirmed by ultraviolet reflectance. The films in the holes seeded by the hydrogen plasma

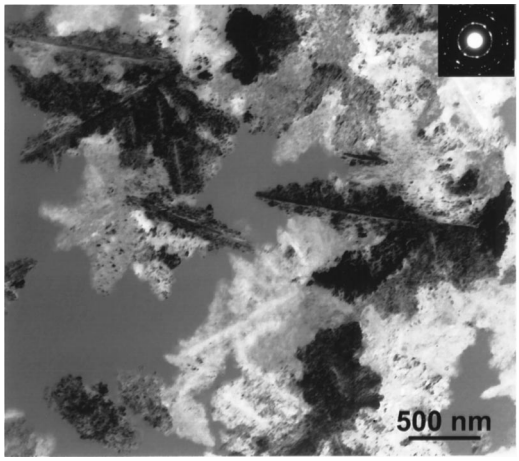

FIG. 2. TEM observation on polysilicon films after anneal at 600 °C for 16 h without hydrogen plasma treatment (control sample) to show a grain size 0.3–0.8 μm. Inset is the diffraction pattern.

are not only completely crystallized, but also laterally grow outward to the surrounding amorphous matrix with a lateral growth rate of 0.5 μm/h. Comparing TEM observations between Figs. 3(b) and 3(d), we can see no grain formed at the area without HPT (control area) until the anneal time increases to 10 h. The grain size at the control area of Fig. 3(d) is ~0.4 μm (indicated by an arrow) in contrast with the ~2.5 μm size of the grain which nucleated from the HPT hole and grew laterally outward from the hole. This result shows that the nucleation site can be controlled by selective exposure to hydrogen plasma, and lateral growth from this site will increase the grain size.

Multiple polysilicon grains were observed by TEM in a hole with 1.0 μm diameter annealed at 600 °C for 5 h (Fig. 4). The grain size is about 0.5 μm. Although crystallization occurs only within the hole region exposed to the hydrogen

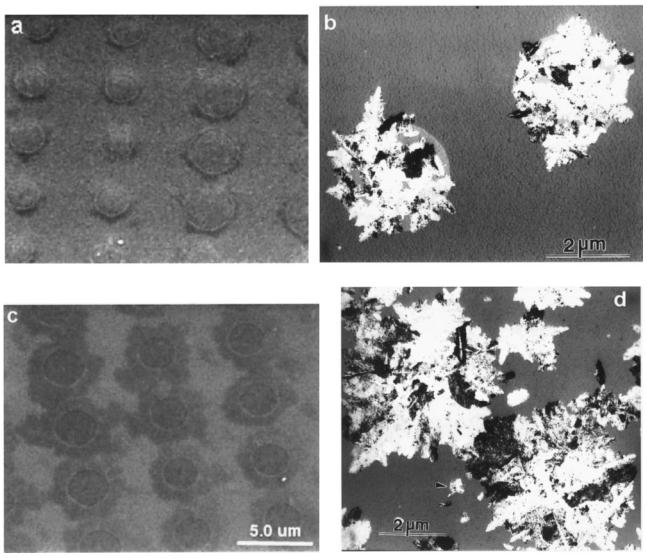

FIG. 3. SEM and TEM micrographs of lateral growth from the nucleation sites induced by hydrogen plasma treatment after 600 °C annealing for: (a), (b) 6 h and (c), (d) 10 h.

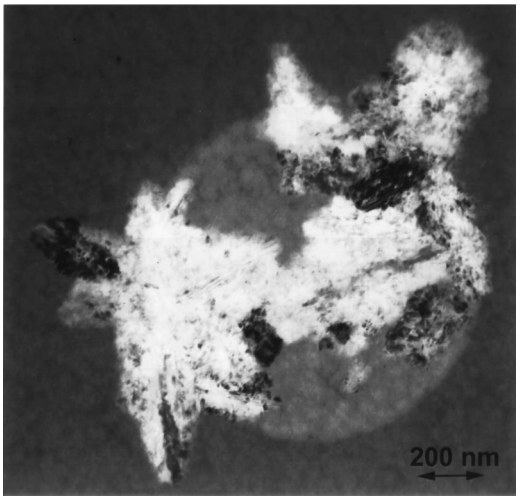

FIG. 4. TEM micrograph of multiple polysilicon grains in a 1.0 μm seeding hole after hydrogenation and annealing at 600 °C for 5 h.

plasma, multiple grains are formed, presumably resulting from multiple nucleation sites. To reduce the number of nuclei, holes with diameters from 0.4 to 1.8 μm were opened in silicon nitride prior to the HPT. After annealing for 3 h at 600 °C, the number of grains in the holes was counted under TEM (Fig. 5). When the hole diameter is greater than 0.8 μm, multiple grains exist in the exposed hole; when the hole diameter is between 0.6 and 0.8 μm, single or multiple grains are observed in the hole, and when the hole diameter is less than 0.6 μm a single-grain island is formed. In the silicon ion implantation approach,[3] the minimum hole size needed to produce a single grain is ~0.66 μm, which is close to our result.

Figure 6(a) shows a single grain within a 0.55 μm diam hole after annealing for 3 h, with approximate dimensions of ~0.13 μm × 0.4 μm. No other grains exist either in the hole or outside of the hole. For longer anneals [8 h, Fig. 6(b)], the grain grows laterally outside of the seeding hole to the amorphous matrix, with the grain size increasing to 0.25 μm × 0.8 μm. The grain size can be as large as 2.5 μm after a 16 h anneal, which is large enough for TFT fabrication. The selective area diffraction pattern (SADP) [Fig. 6(c)] of the silicon grain of Fig. 6(b) confirms the single crystalline nature of the grain. The zone axis of the SADP is the [112] of a face-centered-cubic crystalline structure. The grains are not defect free, however, and the intragrain defects appear by TEM to be similar to those in other polycrystalline silicon films formed by low temperature crystallization of amorphous silicon.

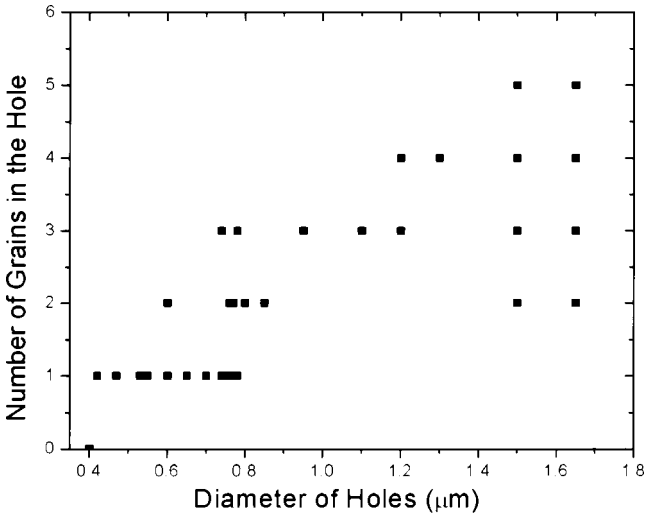

FIG. 5. Relationship between the number of nuclei and the hole size, after hydrogen plasma treatment and annealing at 600 °C for 3 h.

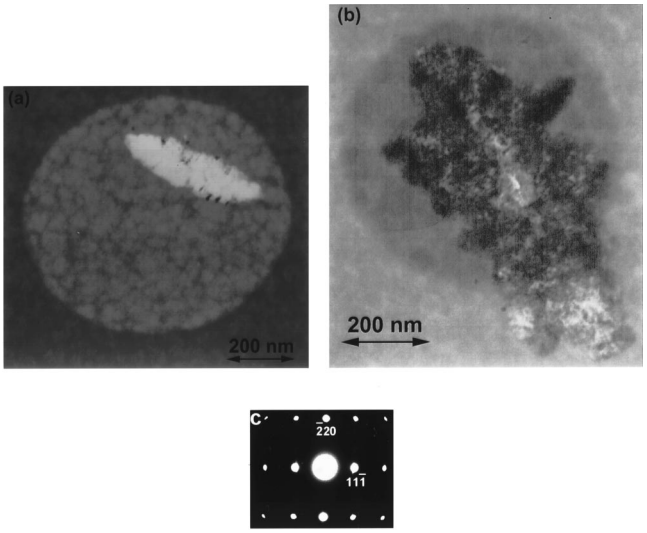

FIG. 6. TEM micrograph of a single nucleus in a hole with a diameter of 0.55 μm, induced by hydrogen-plasma exposure and then annealing at 600 °C for: (a) 3.0 h, (b) 8.0 h, and (c) the SADP of the grain of (b).

IV. CONCLUSIONS

In summary, the location of a single-grain island of silicon can be controlled by the selective exposure of amorphous silicon to a hydrogen plasma, followed by thermal annealing. A simple process using conventional process equipment, no metal addition, and only one mask has been demonstrated. The diameter of the holes opened in the masking layer controls the number of nuclei in the hole and a single nucleus can be induced if the diameter of holes decreases below 0.6 μm. Grains as large as 2.5 μm have been observed.

ACKNOWLEDGMENTS

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