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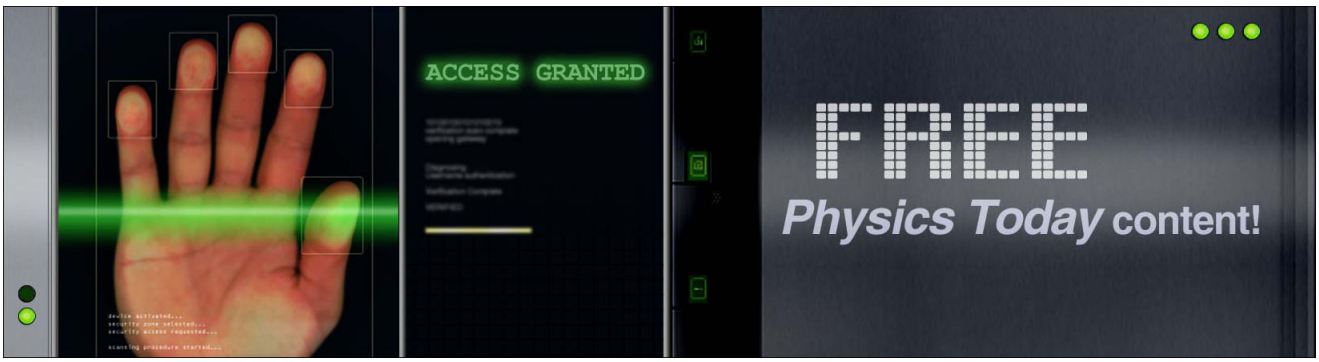

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Microstructure of polycrystalline silicon films obtained by combined furnace and laser annealing

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Amorphous Si films deposited by the low pressure chemical vapor deposition from disilane, and subsequently subjected to a combined furnace annealing at 600 °C/12 h and a sequential excimer laser annealing, results to polycrystalline silicon films with very large grains, low in-grain defect density, and smooth-free surface. Large but heavily defected grains are produced by the furnace annealing, the in-grain defects are mainly microtwins, which are eliminated by a combined liquid–solid state process induced by the laser annealing. The two-step annealing provides a very high quality polycrystalline material suitable for thin-film transistor application. © *1995 American Institute of Physics.*

One of the most successful ways to develop good quality polycrystalline silicon (polysilicon) films in order to fabricate thin film transistors (TFTs) on low cost glass substrates for videographic applications, is by laser crystallization of amorphous silicon (*a*-Si). In most of the cases the *a*-Si is deposited by low pressure chemical vapor deposition (LPCVD) of silane at temperatures around 550 °C and then is annealed by laser.[1] Indeed, the TFTs performances are superior if compared to that of TFTs fabricated on polysilicon films crystallized by annealing in a conventional furnace at temperatures around 630 °C, although the grain size of the latter is several times larger than the size of the former [around 100 nm (Ref. 2)]. This discrepancy is attributed to the density of the in-grain defects.[3,4]

The quality of polysilicon films, which were annealed in a conventional furnace at 630 °C, is significantly improved if a second annealing by rapid thermal process (RTP) is performed for 30 s at temperatures around 800–850 °C.[3,4] Significant improvement of the TFTs performance was also observed by combined furnace and laser annealing.[5] During the RTP process the size of the grains does not change because movement of the grain boundaries occurs above 1150 °C. However inside the grains significant improvement of the structure occurs by elimination of the in-grain defects. These defects are mainly microtwins of first and higher order which are characteristic of the low temperature solid state crystallization in silicon.[6] The twin boundaries can move at temperatures above 750 °C as *in situ* experiments in the transmission electron microscope (TEM) have shown.[4]

In this letter the structure of *a*-Si films subjected to a two step process involving low temperature furnace annealing at 600 °C followed by laser annealing was studied by TEM.

Amorphous Si films, ≈100 nm thick, were deposited by LPCVD method using pure disilane on Corning glass at 550 °C. The films were annealed in a conventional furnace under inert atmosphere at 600 °C for 12 h. Then they were irradiated at different energy densities using a XeCl excimer laser. During the laser annealing the sample was kept in vacuum at 330 °C and a beam homogeneizer was used to produce a uniform 7×7 mm image onto the sample. Amorphous Si films were also subjected only to laser annealing for comparison. Disilane was chosen as the reacting gas for the deposition of the *a*-Si films because it gives a very high rate of growth resulting to a lower density of nucleation centers and consequently to a larger grain size after crystallization.

The structure of the polysilicon films listed in Table I, is also shown in Fig. 1 by the cross-section TEM (XTEM) and the plane view TEM micrographs. From Table I it is evident

TABLE I. Structural characteristics of polysilicon films.

Number of specimen	Laser energy (mJ cm^{-2})	Grain size (nm)	Roughness (nm)	Density of ingrain defects
1A[a]	200	53	15±3	Low
2A	250	140	16±3	Low
3A	280	210	12±3	Low
4A	350	250	16±3	Low
5A	380	285	18±3	Low
0C[b]	No	1200	0	Very high
1C	200	1100	0	Very high
2C	250	1100	0	Very high
3C	280	1150	3±1	High
4C	350	1400	5±2	Medium
5C	380	1500	5±2	Low

[a]Specimens annealed only by laser are denoted by the letter A.
[b]Specimens annealed by furnace at 600 °C/12 h are denoted by the letter C.

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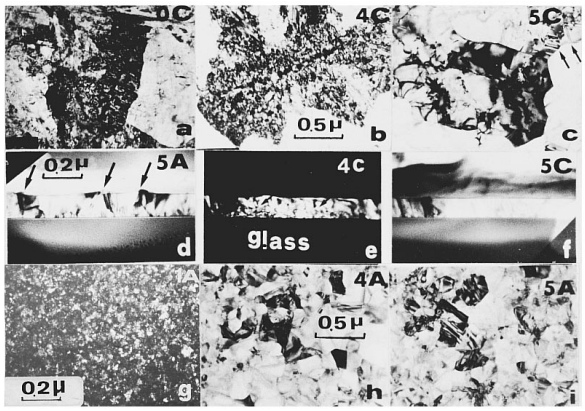

FIG. 1. The structural characteristic of polysilicon films listed in Table I. The specimen number of the film is denoted in upper right-hand corner of the photographs. The plane view micrographs (a), (b), (c), (g), and (h) were taken, for comparison, at the same magnification. (a) Specimen (0C) subjected only to furnace annealing at 600 °C/12 h denoted hereafter (FA). Due to the high density of microtwins a mottlelike contrast is evident. (b) Specimen (4C) which was subjected to FA followed by a laser annealing (LA) at 350 mJ cm^{-2}, the microtwins persist. (c) Specimen (5C), which was subjected to FA plus LA at 380 mJ cm^{-2}. At this stage a dramatic reorganization inside the grains occurs resulting in elimination of the microtwins. No substantial movement of the grain boundaries was observed in this case. (d) XTEM micrograph from specimen (5A), which was subjected only to LA at 380 mJ cm^{-2}. Small grains and higher roughness at the surface are the main characteristics of this film. (e) XTEM dark field micrograph from specimen (4C), which was subjected to FA plus LA at 350 mJ cm^{-2}. Only a single grain of the polysilicon film is diffracting. In the lower part of the grain a high density of defects is evident denoted by arrows. (f) XTEM micrograph from specimen (5C), which was subjected to FA and LA at 380 mJ cm^{-2}. A very large grain, free of defects with smooth-free surface is evident. (g) Specimen 1A, which was subjected only to LA at 200 mJ cm^{-2}. The structure presents a complete crystallization with a grain size around 50 nm. (h) Specimen 4A, which was subjected only to LA at 350 mJ cm^{-2}. The structure presents small grains with a grain size around 250 nm. (i) Specimen 5A, which was subjected only to LA at 380 mJ cm^{-2}. The structure is the same as (h) with a slightly larger grain size.

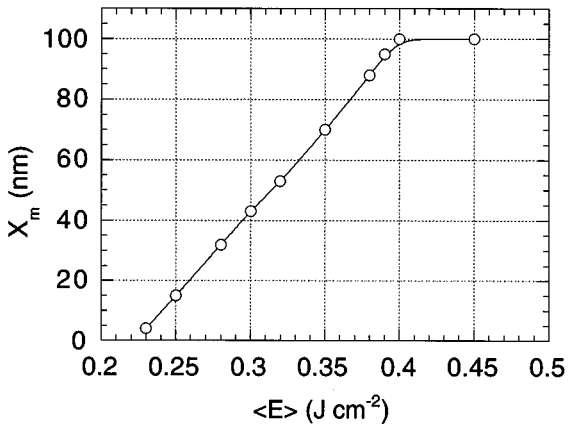

FIG. 2. Calculated molten thickness x_m, vs laser energy density E relative to 100 nm thick polysilicon film on glass.

that the mean grain size of the furnace annealed films is about 1 μm as it is shown in Fig. 1(a). Amorphous silicon films deposited by silane and annealed under the same conditions give a mean grain size 0.25 μm only.[6] Low laser energy densities up to 280 mJ cm^{-2} do not affect the structure of the specimens already annealed at 600 °C. The size of the grains as well as the microtwin density do not change, revealing that the laser energy was not sufficient to activate movement of the twins. In contrast the *a*-Si films are easily crystallized, when irradiated with the same energy densities as it is shown in Table I. A laser energy of the order of 350 mJ cm^{-2} improves the quality of the films previously annealed at 600 °C/12 h, Fig. 1(b). However improvement occurs only in the upper half of the films as it is revealed by the XTEM micrograph in Fig. 1(e). Amorphous Si films which were irradiated only by laser at the same energy are shown in Fig. 1(h). Irradiation by laser at 380 mJ cm^{-2} of the films which were already subjected to a furnace annealing at 600 °C/12 h, results in elimination of the microtwins as it is shown in Figs. 1(c) and 1(f), respectively. Only very few large twins remain, denoted by an arrow in the plane view micrograph in Fig. 1(c). The mean size of the grains is slightly larger than the size of the furnace annealed specimens, Fig. 1(a), revealing that in this case a small movement of the grain boundaries occurs. The small increase of the grain size is attributed to the smoothening of the grain boundaries which for films annealed only at 600 °C are very obscured and consequently they have higher surface energy. Amorphous silicon films annealed only by laser at the same energy density give grains five times smaller as it is shown in Figs. 1(d) and 1(i). The films exhibit significant roughness which appears as protrusions at the grain boundaries revealing significant mass transfer to the boundaries as it shown in Fig. 1(d). This behavior can be understood by considering that the melting point of *a*-Si is roughly 20% lower than that of crystalline Si,[7] and the amorphous to crystalline reaction is exothermic with an energy release of 0.12 eV/atom.[8]

From Table I it is evident that in polysilicon films, which were annealed only by laser, the grain size increases proportionally with the laser energy. In contrast the grain size of the already crystallized films at 600 °C is rather insensitive to the laser energy. The in-grain existing microtwins are activated and start to move above a threshold energy located around 250 mJ cm^{-2}. In order to simulate the thermal process during the laser annealing we used a computer program based on heat flow calculation (HFC).[9] In the simulations the thermal and optical parameters of the polysilicon film were approximated with those of crystalline silicon. In Fig. 2 the molten thickness x_m, is shown versus the laser energy density E. As can be seen, the polysilicon surface starts to melt around 220 mJ cm^{-2} and x_m linearly increases for increasing energy density. This behavior can explain the TEM observation: indeed the onset for the in-grain reordering is close to the energy required for initiating the surface melting. As the energy density increases the microstructure reordering occurs in the region, where the melt–regrowth process occurs. In fact, a laser energy density of 350 mJ cm^{-2} can melt only nearly 60% of the film, leaving most of the microtwins in the lower part as it is shown in Fig. 1(e). Some of them can propagate in the melted part of the films during the recrystallization process counteracting the beneficial effect of the laser annealing. For the film shown in Fig. 1(f) a laser energy density of 380 mJ cm^{-2} was sufficient to melt 80% of the film thickness, leaving only the lower 20 nm of the film in the solid phase. However even in this part the temperature was sufficiently high to eliminate the microtwins leaving a

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perfect seed for the subsequent recrystallization of the upper part of the film. In this way the size of the grains is not appreciably affected but the in-grain defects are eliminated.

It is concluded that very large grains with low density of defects and very smooth-free surface can be formed using as starting material *a*-Si deposited by disilane and subsequently subjected to a combined furnace and laser annealing. To properly combine the beneficial effects of the two annealing techniques, the laser energy density has to be sufficient to melt most of the film. This, in fact, will leave a thin solid layer which acts as seed for the grain regrowth, producing a final structure with large grains, as induced by furnace annealing, with low in-grain defects. The melt–regrowth process induced by laser annealing results in the elimination of the microtwins which are mainly coherent {111} type electrically inactive twins.[10] However most of the coherent twins terminate inside the grains and consequently introduce second order twins which are characterized by a displacement vector and are electrically active as recombination centers. In addition incoherent (112) steps are formed perpendicular to the {111} twin planes introducing dislocations at the step edges which are electrically active.[6] Thus the elimination of the microtwins significantly improves the electrical properties of the films.[3,5] These results provide direct microscopic evidences for the observed improvement in the performances of TFTs fabricated using a combined furnace and laser annealing.[5]

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