Polycrystalline Silicon Produced by Joule-Heating Induced Crystallization

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Abstract — An electric field was applied to a conductive layer to induce Joule heating in order to generate the intense heat needed to carry out the crystallization of amorphous silicon. Complete crystallization was observed via Joule heating under typical processing conditions. Crystallization was accomplished throughout the sample within the range of microseconds of the heating, thus demonstrating the possibility of a crystallization route for amorphous silicon films at room temperature.

Keywords — AMOLED, Crystallization, Joule heating, Polycrystalline silicon, Phase transformation

I. INTRODUCTION

Active matrix organic light emitting diode (AMOLED) has recently come into the spotlight for its applicability to the next-generation flat panel displays. Since the device operates in a current-driven mode uniform source/drain current is critical to guarantee uniform picture quality. Low temperature polycrystalline silicon (poly-Si) is thus preferred to amorphous silicon (a-Si) for the thin-film-transistor backplanes. A crystallization technology should produce poly-Si having a uniform grain size over the whole panel especially for AMOLED application. The methods of forming poly-Si at low temperatures include solid phase crystallization [1], metal induced crystallization [2], metal induced lateral crystallization [3], and excimer laser crystallization (ELC) [4].

We reported a crystallization method named Joule-heating induced crystallization (JIC) [5], using pulsed electric power. In this method, Joule heat is generated by applying an electric pulse to a conductive layer located beneath or above the amorphous silicon film, and is used to raise the temperature of the silicon film to crystallization temperature. For the crystallization of a-Si films to occur, the Joule heat generated must be used mainly in raising the temperature of the film to its crystallization temperature. Thus, an electric field is applied to the conductive layer for a very short time in order to generate intense pulses of energy which are conducted to the film, therefore minimizing the heating of glass substrate.

As the Joule heat is generated uniformly throughout the conductive layer, the temperature of the film can be regarded as being more uniform than that achieved using other conventional heating methods.

In the current work, we utilize a conductive Mo-layer located beneath the amorphous silicon film as a Joule-heat source for JIC crystallization. It was found that the JIC process could produce poly-Si having grain sizes ranging from a few tens of nanometers to greater than several micrometers.

II. EXPERIMENTAL

Schematic diagrams illustrating the constitution of a JIC specimen have been previously reported elsewhere [5, 6]. Using the plasma enhanced chemical vapor deposition (PECVD) method, a SiO2 layer (first dielectric layer) with a thickness of 300 nm was formed on a 0.7 mm-thick glass substrate. A Mo thin film (conductive layer) having a thickness of 100 nm was deposited on the first dielectric layer by sputtering, and then a SiO2 layer (second dielectric layer) having a thickness of 300 nm was deposited thereon using the PECVD method. The PECVD method also resulted in an amorphous silicon thin film having a thickness of 50 nm being deposited on the second dielectric layer. For experimenting the crystallization process in detail, specimens of 20 x 20 mm2 in size and of structures: glass/SiO2/Mo/SiO2/a-Si and glass/SiO2/Mo/SiO2/a-Si/SiO2 were fabricated to investigate crystallization behavior according to the structure of the JIC sample. The sheet resistance of the conductive layer was measured to be ~ 2 Ω/□. A pulsed electric field was applied to a Mo film within the range of a few tens of microseconds for crystallization. Crystallinity was checked using Raman spectroscopy. A Jasco-NR110 Raman system was used at room temperature with the 514.5 nm line from an Ar ion laser. Raman shift was measured between 350 cm−1 and 650 cm−1. Broad peak of a-Si was observed at 480 cm−1 while crystalline Si exhibited a sharp peak at 520 cm−1. The microstructures of the crystallized silicon were examined using scanning electron microscopy (SEM) and bright field transmission electron microscopy (TEM).
III. RESULTS AND DISCUSSION

Figure 1 shows the Raman spectra of JIC poly-Si produced under different processing conditions. In these experiments we used the JIC specimens having the structures of glass/SiO$_2$/Mo/SiO$_2$/α-Si/SiO$_2$. The Raman spectrum shown in Fig. 1(a) corresponds to JIC poly-Si produced by applying a pulsed voltage of 1200 V for 15 μs, while Figs. (b) and (c) show the spectrum of the ones produced by applying pulsed voltages of 1400 V for 15 μs and of 1500 V for 15 μs, respectively. As pulsing voltage increases from 1200 V to 1500 V the Raman spectrum has the more symmetrical shape and FWHM of the Raman spectrum becomes narrower indicating better crystalline quality. Since electric power increases the square of pulsing voltage the peak temperature of a Mo conductive layer approaches to higher values as the pulsing voltage increases resulting in producing polycrystalline silicon with larger grain size.

Figure 2 shows TEM bright field micrographs of the JIC poly-Si for same specimens whose Raman characteristics we compared in Fig. 1. The α-Si film was observed to be fully crystallized according to TEM observation. As can be seen in Fig. 2 the grain size of JIC poly-Si can be varied from tens of nanometers to hundreds of nanometers. It is interesting to note that the JIC poly-Si produced by applying an electric field of 1500 V for 15 μs has the grain size of ~ 500 nm as shown in Fig. 2(c), which is considerably greater than that of typical ELC poly-Si.

Using the JIC specimens of the structure: glass/SiO$_2$/Mo/SiO$_2$/α-Si, we found that crystallization kinetics exhibits completely different behavior compared to that of specimens of the structure: glass/SiO$_2$/Mo/SiO$_2$/α-Si/SiO$_2$. The JIC poly-Si crystallized at 1050 V for 18 μs was observed to be partially crystallized according to scanning electron microscopy as indicated in Fig. 3. Crystalline solids with a circular geometry embedded in an amorphous matrix were observed. This experimental observation that the crystalline solids are formed in a disc shape implies that crystallization proceeds through phase transformation from liquid to solid phases.

As we increased the pulsed voltage to 1150 V with the same pulsing time we observed super-grains having grain size greater than 5 μm as shown in Fig. 4. It is speculated that these super-grains are grown isotropically from the initial seeds located near the grain centers as can be seen in Fig. 4. It should be emphasized that these super-grains are formed by lateral growth mechanism without any artificial control commonly applied in laser-induced crystallization [7].
Thermal deformation resulting in glass bending is another important issue for the practical application of JIC process. Using the commercial FEM software [8] we can estimate the thermal deformation of the backplane during the JIC process in detail. Since the thin-film structure on the glass backplane is too thin to include its thermal behavior in the numerical simulation as well as that for the glass backplane within a limited computation time, only the deformation of the glass has been simulated in this study.

Since the glass geometrically expands with temperatures and the heat-pulse is extremely confined in the upper surface region of the glass, the glass bends upwards during the heating stage. If the deformation during the heating and cooling stages is elastic, the final shape of the glass is the exactly same as its initial shape. Here, the maximum temperature of the glass can go beyond the softening points and thus the deformation is not elastic anymore. Since the yielding phenomenon and viscoelastic properties of the glass at temperatures above the softening points result in the stress relaxation inside the glass, the final shape of the glass after the cooling stage is concaved as observed in the experiments. Figure 5 shows the radii of curvatures of the glass backplane and energy densities with respect to heat-pulse durations for the identical peak temperature of 1200°C. Since shorter pulses result in larger radii of curvature of the glass and demanding lower energy densities, the heating stage should be limited within a very short pulsing time affordable in the JIC facilities.
Fig. 3 SEM micrograph for JIC poly-Si produced by applying a pulsed voltage of 1050 V for 18 μs. Notice that partial crystallization was observed.

Fig. 4 SEM micrograph for JIC poly-Si produced by applying a pulsed voltage of 1150 V for 18 μs.

Fig. 5 Radius of curvatures and energy densities with respect to various heat-pulse durations for $T_{max} = 1200°C$.

IV. CONCLUSIONS

We conducted Joule-heating induced crystallization (JIC) of amorphous silicon using a conductive Mo-layer as a Joule-heat source. We discovered that JIC process could produce poly-Si having grain sizes ranging from several tens of nanometers to greater than several micrometers. Under some processing conditions the super-grains of greater than 5 μm were produced by lateral growth without artificial intervention. This process does not make use of any metallic element inducing preferential nucleation or accelerating crystal growth. Furthermore, the process can be completed within several tens of microseconds at room temperature without serious structural deformation.

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