Surface roughness effects in laser crystallized polycrystalline silicon

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Two surface roughening mechanisms have been distinguished in laser crystallized polycrystalline Si: one is related to rapid release of hydrogen from hydrogen-rich plasma enhanced chemical vapor deposited amorphous Si and the other is independent of the hydrogen content of the material and is determined by the total number of pulses incident on the surface. At, or beyond, the melt threshold energy there is a positive feedback effect between a beam-induced periodic surface roughness pattern and enhancement of this pattern by interference effects in subsequent pulses.© 1995 American Institute of Physics.

There is increasing interest in the use of polycrystalline Si (poly-Si) thin film transistors (TFTs) for large area electronics applications, such as the addressing circuitry in active matrix addressed flat panel displays. The preferred techniques for the formation of poly-Si are by crystallization from amorphous precursor material either by solid phase crystallization at ~600 °C or by laser crystallization. In this letter we discuss the issues concerning surface roughness in excimer laser crystallized poly-Si using both high and low hydrogen content a-Si deposited by plasma enhanced chemical vapor deposition (PECVD) and low-pressure chemical vapor deposition (LPCVD), respectively.

One of the issues with the high hydrogen content material is the controlled release of the hydrogen from the material, which can itself be responsible for unacceptable surface roughening due to blistering of the material. This is most acute with top-hat homogenized beams,1 unless a stepped energy sequence is used to progressively dehydrogenate the material.2 We have shown that these problems can be removed by mechanically scanning the plate through a laser beam with a semi-Gaussian energy distribution.1 However, in terms of throughput and uniformity there are issues of scan rate: the faster the scan rate the higher the throughput, but in terms of throughput and uniformity there are issues of scan terms there is a positive feedback effect between a beam-induced periodic surface roughness pattern and enhancement of this pattern by interference effects in subsequent pulses.© 1995 American Institute of Physics.

The crystallization was carried out with a 248 nm KrF excimer laser, using a crystallization system with, as previously described,1 semi-Gaussian pulses. The beam had a full width at half-maximum (FWHM) of 6.6 mm and the samples were scanned in the direction of the Gaussian energy distribution.

The two types of layer used in the work were 150 nm thick films deposited either by PECVD at 250 °C or by LPCVD at 540 °C. The deposition rates were ~25 nm/min and 0.7 nm/min, respectively, and the hydrogen concentrations measured by secondary ion mass spectrometry (SIMS) were $4.5 \pm 1.5 \times 10^{21}$ cm$^{-3}$ and $\sim 2 \times 10^{19}$ cm$^{-3}$, respectively. The laser-induced crystallization was assessed by measuring the height of the surface reflectance peak at 275 nm.1,3 A reflectance peak at this wavelength is characteristic of crystalline silicon4 and its height is a qualitative measure of crystallinity. A qualitative and comparative measure of surface roughness was obtained from the surface reflectivity at 234 nm,1,5 (a reflectivity of 100% relative to polished crystalline silicon representing perfect smoothness).

For incident energies sufficient to achieve maximum crystallization of the film,1,3 the surface roughness, as monitored by surface reflectance at 234 nm, had the dependence on plate scan speed (or the number of pulses/mm) as shown in Fig. 1. At low scan speeds (equivalent to a large number of pulses per mm) both PECVD and LPCVD (curves A and B) display increased surface roughening, whilst at high scan speeds only the PECVD Si experienced increased roughening. Hence, there are two distinct roughening mechanisms occurring during laser crystallization: one is only seen in PECVD Si and is hydrogen related; the other is related to the total number of pulses and is independent of the hydrogen content of the material. The significant difference between the two types of material was confirmed to be the hydrogen content, as indicated by the PECVD amorphous Si (a-Si) (curve C in Fig. 1) which, following a thermal dehydrogenation anneal for 1 h at 500 °C, behaved like the LPCVD a-Si. The results in Fig. 1 were for a particular value of pulse energy density. Figure 2, showing constant surface roughness contours for LPCVD Si, illustrates the interdependence of the peak pulse energy and pulse density in determining roughness. This

![Graphical representation](image)

**FIG. 1.** Variation of surface roughness, indicated by surface reflectance at 234 nm, with laser scan speed for (A) PECVD, (B) LPCVD, and (C) dehydrogenated PECVD a-Si. Peak irradiation energy densities were 172, 250, and 245 mJ/cm$^2$/pulse, respectively.
shows that the higher the pulse energy density, the lower is the pulse density at which a given degree of surface roughening occurs. To identify the mechanisms responsible for these results, the samples were examined by scanning electron microscopy. Figures 3(a)–3(d) present images of the surface of the LPCVD Si as a function of the number of pulses/mm. At pulse densities of 10/mm and greater, a regular periodic pattern is seen with a pitch of \( \sim 0.25 \, \mu \text{m} \). This pitch is very similar to the wavelength of the light and is an indication of a dose dependent interference effect of the type described for other laser/material systems, and referred to as laser induced period surface structures, LIPSS. For light at normal incidence, any incipient roughness which satisfies the Rayleigh diffraction condition:

\[
\lambda = d n,
\]

where \( d \) is the grating period (or roughness pitch) and \( n \) is the refractive index of the medium above the surface, will give a first-order diffracted wave parallel to the sample surface. Interference between this wave and the incident wave leads to a periodic variation in the radiation intensity coupled into the surface. Providing the energy maxima are sufficient to modify the surface, by, for instance, local melting and surface tension effects, a further growth of the self-induced grating can occur. As seen in Fig. 3(d), this ultimately leads to considerable texturing of the sample surface. Figures 3(e) and 3(f) show two extreme pulse densities for the PECVD silicon: at 100 pulses/mm surface texturing due to the self-induced grating effect is seen as with the LPCVD Si. At the low pulse density of 1 pulse/mm, the surface roughness is quite different and the microscopic blistering of the surface is due to the rapid release of hydrogen from the film. As shown in Fig. 1, this effect is avoided at higher pulse densities due to the more controlled and progressive heating of a given area by finely incremented energies as the region is scanned by the leading edge of the Gaussian beam. This will thermally dehydrogenate the film prior to irradiation by the peak beam intensity which melts the film.

The interference fringes run across the width of the scanned stripe, which is perpendicular to the direction of the Gaussian energy distribution and perpendicular to the direction of the radiation \( E \) vector. The beam used for the results shown in Fig. 3 was partially polarized due to the type of attenuator used to control the incident energy density. Beam polarization has been previously reported to influence the formation of ripple patterns and this was confirmed with the a-Si samples by comparing results with fully polarized and nonpolarized beams. At 252 mJ/cm²/pulse and 20 pulses/mm only the polarized beam led to the formation of unambiguous, long range ripple patterns. Again the interference ripples were perpendicular to the \( E \) vector.

We have recently reported that irradiations in air led to greater surface roughening than irradiations in an inert ambient. This was tentatively attributed to the presence of oxygen and this conclusion has been confirmed by the results shown in Fig. 4. Surface roughening, as monitored by the surface reflectance at 234 nm, progressively increases with oxygen content in the crystallization ambient for a given pulse energy density. Scanning electron microscopy (SEM) examination of these samples showed gross surface roughening similar to that shown in Fig. 3(f), but there was no indication of this displaying the periodicity seen with the inert ambient anneals. At the moment, the role of oxygen in stimulating this effect is unclear, but from a practical point of view, the use of a vacuum for crystallization is clearly beneficial.

In conclusion, two surface roughening mechanisms have been identified in laser crystallized poly-Si; one is related to the release of hydrogen from hydrogen-rich PECVD a-Si, and the other is independent of the hydrogen content of the
material and is governed by the total number of pulses incident on the surface, with energies above the melt threshold. With a partially or fully polarized beam, there is a positive feedback effect occurring in this situation with interference between the incident wave and a surface diffracted wave leading to a long range periodic surface roughness pattern which progressively enhances the interference effect with each subsequent pulse.

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