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Photocarrier diffusion lengths of high-growth-rate microcrystalline silicon

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Abstract

We report on photocarrier transport of high-growth-rate microcrystalline Si (μc-Si) in conjunction with the lateral size, σ_L, of crystallites' conglomerate (grain) determined from the atomic force microscope (AFM) topographic images on the basis of fractal concepts. μc-Si films were prepared using very-high-frequency plasma-enhanced chemical vapor deposition at a high deposition rate of 6.8 ± 0.5 nm/s. μc-Si thicknesses, d, were varied from 0.53 μm to 5.6 μm. With an increase in d, σ_L increased from 70 nm to 590 nm. At the same time, the ambipolar diffusion lengths, L_{amb}, of photocarriers, observed using the steady-state photocarrier grating (SSPG) technique, increased from 50 nm to 420 nm. Log–log plots of L_{amb} versus d and σ_L versus d were both expressed as a power law with an exponent of 0.9, yielding a simple linear relation between L_{amb} and σ_L. Moreover, their ratio, L_{amb}/σ_L, was below unity, implying the intra-grain carrier diffusion. From these results, the role of the grain (column) boundaries for photocarrier diffusion in μc-Si is discussed.
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1. Introduction

Microcrystalline silicon (μc-Si) is a promising material for device applications, particularly for photovoltaic applications [1]. High-rate-growth (>1 nm/s) of μc-Si is of current importance in achieving high-throughput manufacturing [2–5]. We have revealed the structural features of high-growth-rate μc-Si, which are basically identical with those of low-growth-rate μc-Si [5,6]: the columnar structures near the amorphous-crystalline phase transition region. μc-Si surfaces also comprise of the dome-shaped column-heads, which are conglomerates of nanoscale crystallites.

The grain (column) boundary has been suggested to be crucial in determining the macroscopic photocarrier transport [7,8]. Nevertheless, the influence of grain boundary has not been revealed systematically, even associated with low-growth-rate μc-Si, because the grain boundary seems quite complicated due to the fractal (self-similar) structure of μc-Si [9]. In order to discuss the effects of grain boundary, the line-shape of grain boundary must be identified. From the converse viewpoint, the lateral size of grains must be determined. Recently, we have demonstrated that the lateral size of grains can be derived from fractal concepts; the lateral size is defined as twice the lateral correlation length of surface heights measured using an atomic force microscope (AFM) [10,11].

In this article, the lateral size, σ_L, of crystallites' conglomerate (grain) [7,8] is presented employing high-growth-rate μc-Si, together with the ambipolar diffusion length, L_{amb}, of photocarriers observed using the steady-state photocarrier grating (SSPG) technique [7,8,12,13]. The role of grain boundary for the photocarrier diffusion is discussed from L_{amb} and σ_L taking from μc-Si with different thicknesses.

2. Definition of lateral size

The lateral size of grains, σ_L, is defined from the height–height correlation function, $H(r)$, as expressed by [14]:

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$$H(r) = \langle (h(r') - h(r' + r))^2 \rangle_{r'}, \tag{1}$$

where $h(r')$ denotes the surface height at position r', r is the length between the two points. The angular bracket stands for its statistical average. Generally, $H(r)$ is expected to scale as

$$H(r) \sim \begin{cases} r^{2\alpha} & (r \ll \xi) \\ 2w^2 & (r \gg \xi), \end{cases} \tag{2}$$

where ξ denotes the lateral correlation length, α the roughness exponent, w the surface width (rms surface roughness) [14]. Here, we define the lateral size of grains as $\sigma_L = 2\xi$ [10,11].

3. Experimental details

Undoped μc-Si films were prepared on Corning 1737F glass substrates using very-high-frequency (VHF) (100 MHz) plasma-enhanced chemical vapor deposition [5,6]. The deposition conditions were basically identical with those of the *i*-layer of a 5% efficiency solar cell [6]: substrate temperature of 180 °C, deposition pressure of 2.4 kPa, VHF power of 2.2 W/cm^2, silane flow rate of 10 sccm, and hydrogen flow rate of 657 sccm. The deposited samples were annealed at 150 °C in N_2 ambient for 1 h.

The film thicknesses in the range of 0.56–5.3 μm were measured using a stylus profiler (Sloan Dektak3ST), and the growth rate was estimated as 6.8 ± 0.5 nm/s. The crystalline fractions of 38–61% were obtained using a microscopic Raman scattering system equipped with a 514.5 nm Ar^+ ion laser (Renishaw System 1000).

For the SSPG measurement, a He–Ne laser (633 nm, 15 mW) was used to measure small-signal photocurrents at 3 V dc bias voltages between the coplanar contacts with a gap of 1 mm. The laser light beam was split into two light beams, and the modulated light beam and the dc bias light beam were applied simultaneously on the gap with different angles. The intensity ratio of modulated light beam to dc bias light beam was 1:20, and the modulation frequency was 40 Hz [13]. The polarization angle of dc bias light was changed using a half-wave plate, then the modulated component of coplanar photocurrent is measured with a lock-in technique, both when the two light beams are coherent, ΔJ_{par}, and when they are non coherent, ΔJ_{perp}, respectively, for different grating periods. The dark conductivities were in the range of 4.5×10^{-8}–1.2×10^{-6} S cm^{-1}.

The surface widths of the μc-Si films were obtained from topographic images taken by a AFM system (SII SPA400/SPI3800N) using tapping-contact mode [9]. Scan sizes were changed between 1 × 1–5 × 5 μm^2; the data points were 256 × 256. The tip radius of the cantilever was ⩽15 nm.

4. Results

Fig. 1 shows typical AFM topographic images of μc-Si surfaces taken with differing d. The lateral sizes σ_L were estimated as (a) 70 nm, (b) 240 nm, and (c) 590 nm, respectively. The lower curve in Fig. 2 shows $\log w$ versus $\log d$ plots, and w is expressed as $w(d) \sim d^{\beta}$ [14] with the roughness exponent β of 0.84. In Fig. 2 (upper curve), $\log \sigma_L$ versus $\log d$ plots are depicted, and σ_L is expressed as $\sigma_L(d) \sim d^{1/z'}$ with the scaling factor $1/z'$ of 0.92.

The ambipolar diffusion length, L_{amb}, is estimated from the standard method [12]. Fig. 3 shows typical plots of the ratio, β^{SSPG}, defined as $\Delta J_{per}/\Delta J_{prep}$ plotted as a function of the grating period, Δ, for high-growth-rate μc-Si films.

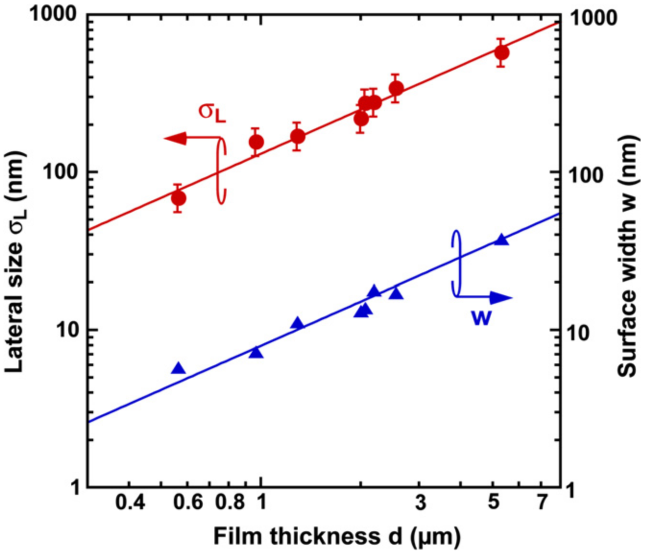

Fig. 2. Log–log plots of the lateral sizes σ_L (●) and the surface widths w (▲) versus film thicknesses d for μc-Si films. Solid lines exhibit the least square fittings to $\sigma_L \sim d^{0.92}$ and $w \sim d^{0.84}$, respectively.

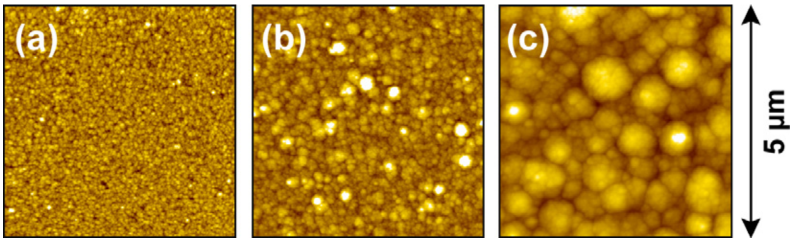

Fig. 1. AFM surface images of μc-Si films with differing film thickness d [(a) 0.56 μm, (b) 2.1 μm, and (c) 5.3 μm]. The lateral sizes σ_L were estimated as (a) 70 nm, (b) 240 nm, and (c) 590 nm, respectively.