Free carrier optical absorption used to analyze the electrical properties of polycrystalline silicon films formed by plasma enhanced chemical vapor deposition

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Abstract

The electrical properties of (400) oriented polycrystalline silicon films fabricated at 300°C by 100-MHz plasma enhanced chemical vapor deposition from gaseous mixture of \( \text{SiF}_2/\text{H}_2/\text{SiH}_4 \) are reported. A double layered structure of phosphorus-doped poly-Si/\( \text{H}_2/\text{F} \) film (200 nm)/undoped poly-Si/\( \text{H}_2/\text{F} \) film was adopted to research the changes in electrical properties in the doped layer induced by the undoped layer thickness. The carrier mobility in the crystalline grain of the doped layer, analyzed by free carrier optical absorption, increased from 10 to 35 cm\(^2/V\text{s}\) as the undoped film thickness increased from 0 to 1000 nm. The carrier density in the crystalline grain was \( 2.5 \times 10^{20} \text{ cm}^{-3} \) for each sample. The grain properties in the doped layer improved as the undoped film thickness increased.

Keywords: VHF(100 MHz) PECVD; Poly-Si/\( \text{H}_2/\text{F} \); Double-layered structure; Free carrier optical absorption; Electrical conductivity; XeCl excimer laser

1. Introduction

Polycrystalline silicon films (poly-Si) fabricated at low temperatures (< 400°C) are important for device applications such as solar cells and thin film transistors. Plasma enhanced chemical vapor deposition (PECVD) has the advantage of uniform film formation over a large area at a low temperatures. The poly-Si/\( \text{H}_2/\text{F} \) films fabricated at low temperatures (≤ 300°C) from \( \text{SiF}_2/\text{H}_2 \) mixing gases using very high frequency PECVD were reported to have large grain sizes (> 100 nm in diameter) and a high electron mobility (~ 10 cm\(^2/V\text{s}\)) [1–4]. The analysis of free carrier optical absorption gives the carrier mobility and density in the crystalline grain, because free carrier optical absorption occurs via the excitation induced by the electrical field of incident photons, followed by energy relaxation in the crystalline grains [5–10]. Besides, electrical conductivity is analyzed with electrons traversing crystalline grains and grain boundaries. It depends on the grain boundary properties.

In this paper, we have reported the electrical properties at the leading surface region of film growth using a doped poly-Si/\( \text{H}_2/\text{F} \) film/undoped poly-Si/\( \text{H}_2/\text{F} \) film double-layered structure with different undoped film thickness. Also, in order to reduce defect states in the crystalline grain and grain boundary, a XeCl excimer laser was irradiated. The electrical properties after laser irradiation were discussed.

2. Experiment

The poly-Si/\( \text{H}_2/\text{F} \) films were formed on quartz glass by 100-MHz plasma enhanced chemical vapor deposition from \( \text{SiF}_2 \) and \( \text{H}_2 \) mixing gases, as reported [1,2]. Small amounts of \( \text{SiH}_4 \) were added to the mixing gases to increase growth rate. The (400) oriented phospho-
rus-doped films were fabricated at 300°C, 20 W and SiF₆/H₂/SiH₄ = 60/3.0/0.1 sccm. The PH₃ gas concentration was used between 0.2 and 40,000 ppm. In order to investigate the electrical properties in the doped layer which are dependent on underlying film thickness, we adopted a double-layered structure. The top P-doped layer thickness was 200 nm. The bottom undoped layer thickness was varied from 0 to 1000 nm. The free carrier optical absorption was measured using conventional Fourier transform infrared spectroscopy (FTIR Bomem MB-100) between 400 and 4000 cm⁻¹. The carrier mobility and density in the crystalline grains were obtained by best fitting of experimental and calculation reflective spectra. These samples were irradiated by a 28-ns-pulsed XeCl excimer laser from the top region at room temperature and 1 × 10⁻⁴ Pa. Multiple step laser energy irradiation was carried out. The laser energy density was increased from 160 to 550–600 mJ/cm² in 40-mJ/cm² steps. Five pulses were irradiated at each laser energy density step.

3. Results and discussion

The carrier mobility in the crystalline grain (μₑቔ) of doped layer was analyzed by free carrier optical absorption. The μₑቔ increased from 10 to 35 cm²/Vs as the undoped poly-Si/H/F film thickness increased from 0 to 1000 nm. The crystalline grain properties improved as the undoped film thickness increased. The μₑቔ for a 1000-nm undoped film thickness was close to the carrier mobility of doped single crystalline silicon. A good quality crystalline film was grown on the thick undoped film. Fig. 1(a) shows that μₑቔ depended on temperature and that of 5 × 10⁻²⁰ cm⁻³-doped poly-Si films annealed at a laser energy density of 360 mJ/cm². The μₑቔ of poly-Si/H/F double-layered structures decreased by ~1 cm²/Vs for each sample as the temperature increased from room temperature (RT) to 200°C. Besides, the μₑቔ value of the laser crystallized silicon film was higher than that of the poly-Si/H/F double-layered structure and decreased by ~5 cm²/Vs. The reduction of carrier mobility is an effect of carrier scattering caused by lattice vibration. This result indicates that crystalline grains for doped poly-Si/H/F have density defects compared with laser crystallized silicon films. Fig. 1(b) shows the changes in μₑቔ depending on the temperature after laser irradiation. The μₑቔ values increased in the case of thin undoped film thickness. Even after laser irradiation, μₑቔ for each sample didn’t decrease as the temperature increased, in comparison with laser crystallized silicon films shown in Fig. 1(a). The defects in the crystalline grain remained even after laser irradiation. The crystalline volume fraction at the top surface of the doped poly-Si/H/F film was analyzed from an E₁ peak height of approximately 276 nm, because the E₁ peak gives the crystalline state at a surface region 10 nm deep due to a large optical absorption for silicon (~10⁻⁶ cm⁻¹). It increased from 0.3 to 0.7 for each sample after laser irradiation. The value of single crystalline silicon is 1 and amorphous silicon is 0. In spite of the equal crystalline volume fractions at the surface region for each sample, μₑቔ values were different, as shown in Fig. 1(a,b). This result reveals the distribution of crystalline states in the vertical direction of doped poly-Si/H/F.

In order to estimate grain boundary properties of doped poly-Si films/H/F, we adopted the ratio of σₑቔ to σₑቔ (σₑቔ/σₑቔ). The σₑቔ value is electrical conductivity in the crystalline grain. It was calculated by enₑቔμₑчёт, where e is the electrical primitive charge and nₑቔ is the carrier density in the crystalline grain. The nₑቔ value was analyzed at approximately 2.5 × 10⁻²⁰ cm⁻³ for each sample. It did not change as temperature increased before and after laser irradiation. The σₑቔ value is the effective conductivity measured by electrical measurement with aluminum gap electrodes with a length of 6 mm and an applied voltage of 1 V. In Fig. 2, the ratio before and after laser irradiation in the case of 0 and 1000-nm undoped film thickness are shown. The ratio depended on tempera-
structure fabricated by 100-MHz plasma enhanced chemical vapor deposition. The carrier mobility in the crystalline grain ($\mu_{FCA}$) increased from 10 to 35 cm$^2$/Vs as the undoped film thickness increased from 0 to 1000 nm. A good quality crystalline grain was grown on thick undoped film. The $\mu_{FCA}$ for each sample decreased by $\sim$1 cm$^2$/Vs as the temperature increased from room temperature to 200°C before and after laser irradiation. The defects in the crystalline grain remained for each sample even after laser irradiation, in comparison with that of the laser crystallized silicon film because the $\mu_{FCA}$ of the laser crystallized silicon film was higher and decreased by $\sim$5 cm$^2$/Vs. The grain boundary properties of doped poly-Si films were estimated by the ratio of electrical conductivity in the crystalline grain to effective conductivity ($\sigma_{\text{grain}}/\sigma_{\text{eff}}$). The ratio depended on temperature for the 1000-nm undoped film thickness, showed 5.68 to 5.23 before laser irradiation. After laser irradiation, it showed 3.73 to 3.67. The average energy barrier height decreased from 52 to 34 meV. The ratio of temperature dependence did not change more drastically than for that of the 0-nm thickness of undoped film before and after irradiation. The thermal carrier increased by less than for the 0-nm film thickness. The grain and grain boundary properties improved as the undoped film thickness increased.

4. Summary

We investigated the electrical properties of doped poly-Si/H/F/undoped poly-Si/H/F double-layered...