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Electrical Properties of Excimer-Laser-Crystallized Lightly Doped Polycrystalline Silicon Films

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The electrical properties of excimer-laser-crystallized lightly phosphorus-doped polycrystalline silicon films were investigated. The electrical conductivity of the films increased from 6.0×10^{-7} to 2.3×10^{-1} S/cm as the laser energy density increased from 235 to 436 mJ/cm^2 because the carrier concentration varied from 1.0×10^{11} to 1.8×10^{17} cm^{-3}. In contrast, the carrier mobility was 37.3 and 8.7 cm^2/V·s at low- and high-laser-energy regimes, respectively, and showed a minimum value of 0.24 cm^2/V·s at the intermediate laser energy density of 315 mJ/cm^2. These results can be well explained by a model featuring the localization of trap states at the grain boundary.

KEYWORDS: polycrystalline silicon, laser crystallization, excimer laser, thin-film transistor, Hall effect, carrier concentration, carrier mobility, trap state density

1. Introduction

There is considerable interest in low-temperature-process polycrystalline silicon thin-film transistors (poly-Si TFTs) because they have the possibility of realizing high-performance electronic devices on any insulating substrate. One of the key technologies in poly-Si TFT fabrication is the laser crystallization of silicon thin films. Since laser crystallization is a rapid melt and growth process, it allows us to use low-deformation-point glasses or plastics for the substrates.[1)] In addition, there have been several reports indicating that laser-crystallized poly-Si films can realize TFTs with very high electron mobilities of 400 to 600 cm^2/V·s.[2,3)]

Although many studies have been done on evaluating the electrical characteristics of laser-crystallized poly-Si films by fabricating TFTs, the characteristics of as-laser-crystallized poly-Si films have not been clarified yet. In this paper, we report on the investigation of the electrical properties of as-laser-crystallized poly-Si films. It is shown, for the first time, that light doping of impurities enables us to examine the electrical characteristics of films with very high sensitivity. Also, the crystalline properties of the films are discussed based on a localized-trap-states model.

2. Experiment

Amorphous silicon (a-Si) films 50 nm thick were formed on quartz substrates by the dissociation of Si_2H_6 gas at 425°C using low-pressure chemical vapor deposition (LPCVD). Phosphorus atoms were implanted directly into the a-Si films with the acceleration voltage of 20 kV, and the average doping concentration was expected to be about 1.0×10^{18} cm^{-3}. After removing the native oxide on the a-Si film surface using HF solution, films were crystallized by irradiating them with a XeCl excimer laser in a vacuum chamber at room temperature. The wavelength of the laser light was 308 nm and the pulse duration was 25 ns. The laser beam was transformed to a 10 mm × 10 mm square by using fly-eye-type homogenizer optics with the uniformity of 3% (σ/mean). To determine the laser energy density at the film surface, about 2% of the incident laser beam was split and its focusing beam profile and intensity were diagnosed using a CCD beam profiler and a joule meter, respectively. The laser-crystallized poly-Si films were then patterned and aluminum electrodes were fabricated to perform electrical measurements. Prior to the electrical measurements, the samples were annealed at 300°C in air. The Van der Pauw method was applied for the Hall effect measurement.

3. Experimental Results

Figure 1 shows the electrical conductivity of as-crystallized poly-Si films with respect to the irradiated laser energy density. Excimer laser irradiation was started with low energy density near the crystallization threshold (160 mJ/cm^2), then the energy density was increased stepwise with increments of about 20 mJ/cm^2 (step-up irradiation). At each step, the laser was irradiated five times. The data points are plotted with respect to the average laser energy density at the final step. The electrical conductivity is 6.0×10^{-7} S/cm at a low laser energy density of 235 mJ/cm^2, and it increases more than five orders of magnitude to 2.3×10^{-1} S/cm as the laser energy density is increased to 436 mJ/cm^2. Once microcrystallization occurs at the laser energy density higher than 450 mJ/cm^2, the electrical conductivity falls about five orders of magnitude. Based on this result, the optimum laser irradiation condition can be determined with very high sensitivity. Through careful examination, the laser energy density of 430 to 445 mJ/cm^2, but no higher than 450 mJ/cm^2, was found to give the best-quality poly-Si films using our equipment.

The same samples were then examined by the Hall effect measurement and the result is shown in Fig. 2. When the laser energy density is 235 mJ/cm^2, the carrier concentration is 1.0×10^{11} cm^{-3}, which is close to the intrinsic carrier concentration, then it increases rapidly with increasing laser energy density. As the laser energy density increases beyond 350 mJ/cm^2, the carrier concentration becomes saturated. At the optimum laser irradiation condition of 436 mJ/cm^2, the carrier concentration is 1.8×10^{17} cm^{-3}. When a laser energy greater than 450 mJ/cm^2 is irradiated, the carrier concentration decreases again. This result confirms that the abrupt change in electrical conductivity of as-crystallized poly-Si films is mainly caused by the change in carrier concentration. On the other hand, the carrier mobility shows a very interesting behavior. The as-crystallized poly-Si film shows a high carrier mobility of 37.3 cm^2/V·s at a low laser energy density of 235 mJ/cm^2. It decreases with increasing laser energy density, shows a minimum value of 0.24 cm^2/V·s at

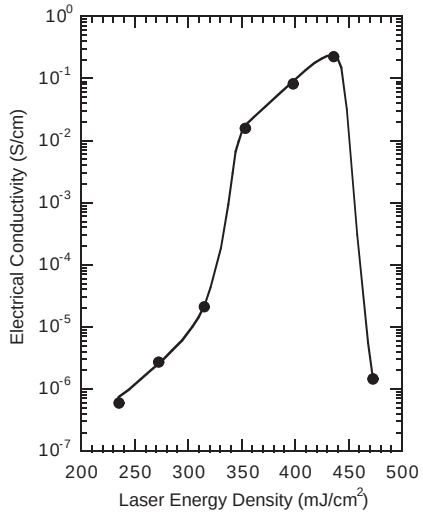

Fig. 1. Variation of electrical conductivity, with respect to the irradiated laser energy density (step-up irradiation).

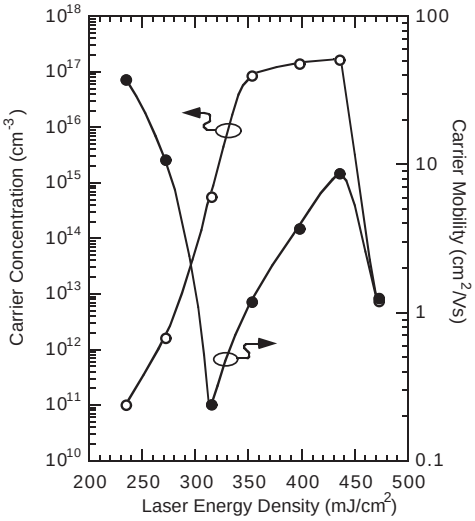

Fig. 2. Carrier concentration and carrier mobility obtained by the Hall effect measurement, with respect to the irradiated laser energy density (step-up irradiation).

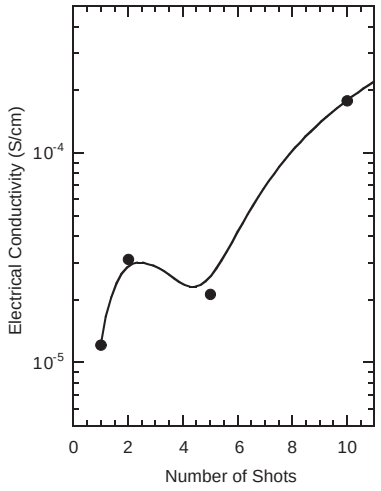

Fig. 3. Variation of electrical conductivity, with respect to the number of laser shots (320 mJ/cm^2).

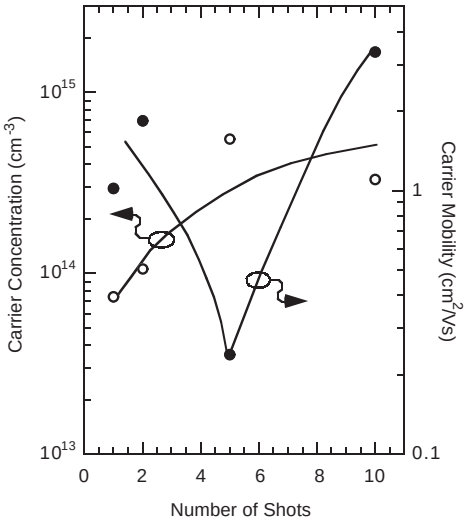

Fig. 4. Carrier concentration and carrier mobility obtained by the Hall effect measurement, with respect to the number of laser shots (320 mJ/cm^2).

315 mJ/cm^2, and then increases with the laser energy density until the microcrystallization threshold. Under the condition of 436 mJ/cm^2 laser irradiation, the carrier mobility was 8.7 cm^2/V·s.

Figure 3 shows the electrical conductivity of poly-Si films with respect to the number of laser shots. The step-up irradiation was applied to the laser energy density of 320 mJ/cm^2 and the number of shots at each step was varied from one to ten. The electrical conductivity increases with increasing laser energy density, except for a drop at five shots.

These samples were also examined by the Hall effect measurement, and the result is shown in Fig. 4. The carrier concentration increases from 7.4×10^{13} to 3.3×10^{14} cm^{-3} as the number of laser shots is increased. The carrier mobility shows a behavior similar to the result in Fig. 2. It decreases as the number of laser shots is increased from one to five, shows a minimum value at five shots, then increases with increasing number of laser shots. The number of laser shots is also important in the electrical characteristics of the poly-Si films.

4. Discussion

To understand the results presented above, we introduce several assumptions. First, we assume that the donor atoms are totally ionized by laser crystallization. Since many works on laser doping have verified the high efficiency of impurity activation,[4] this is an acceptable assumption. Second, we assume that crystallites of the poly-Si films have very low trap state density inside the grain, and that most trap states are localized at the grain boundary. As we recently reported concerning the examination of laser-crystallized poly-Si films by free-carrier optical absorption analysis,[5] we believe that carrier transfer in the laser-crystallized poly-Si films is governed by the grain boundary. Third, those trap states at the grain boundary are assumed to be initially neutral and to become charged by trapping carriers.

By the localized-trap-states model described above, the results shown in Fig. 2 are well explained. Figures 5(a) to 5(c) schematically show the variation of the trap state density and the resulting band diagram with respect to increasing laser energy density. Here, N_t is the trap state density per unit area,

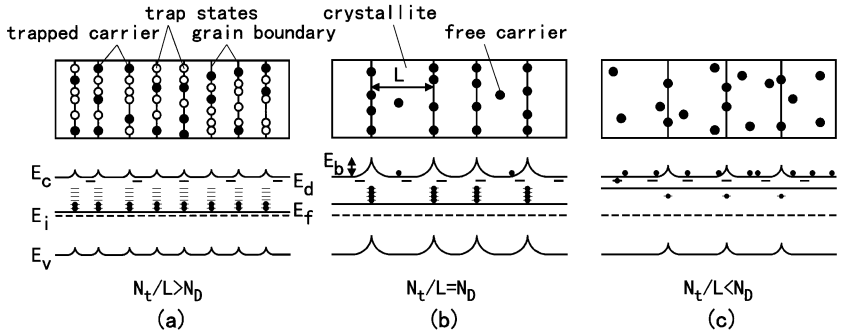

Fig. 5. Schematic diagram of localized-trap-states model and corresponding band structure. Along with increasing laser energy density, the band structure varies from (a) to (c).

L is the average grain size, N_D is the donor concentration, n is the carrier concentration, μ is the carrier mobility, and E_b is the potential barrier height at the grain boundary. When the laser energy density is low because of the small grain size L and the poor grain boundary, the trap state density per unit volume N_t/L is much larger than the donor concentration N_D. Under this condition, as shown in Fig. 5(a), almost all carriers are trapped by the trap states at the grain boundary, and complete depletion occurs inside the grain, resulting in a carrier concentration n close to that of intrinsic silicon. It is possible to attribute the low carrier concentration in the low-laser-energy regime to insufficient activation of the impurities. Based on a calculation of the impurity profile, this effect may reduce the efficiency of impurity activation to 3%. Since this result cannot explain the carrier concentration of 10^{11} to $10^{12}\,\mathrm{cm}^{-3}$ in the low-laser-energy regime, the major origin of low carrier concentration is carrier trapping. Because the trap states are not completely filled under these conditions, the potential barrier height E_b is relatively low. This can explain the result that a relatively high mobility of $37.3\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$ was observed at a low laser energy density of $235\,\mathrm{mJ/cm}^2$. As the laser energy density increases, the trap state density per unit volume N_t/L decreases and the number of carriers excited to the conduction band increases. Along with this, the potential barrier height and width increase because the trap states at the grain boundary are mostly filled, as shown in Fig. 5(b). According to Seto,[6] the potential barrier height E_b takes the maximum value when the trap state density per unit volume N_t/L is identical to the donor concentration N_D. Since the minimum carrier mobility of $0.24\,\mathrm{cm}^2/\mathrm{V\cdot s}$ was observed when the laser energy density was $315\,\mathrm{mJ/cm}^2$, as indicated in Fig. 2, the barrier height E_b was highest under this condition. By a secondary ion mass spectroscopy analysis, the donor concentration was estimated to be $9.5 \times 10^{17}\,\mathrm{cm}^{-3}$, and a transmission electron microscopy analysis revealed the average grain size of this poly-Si film to be about 56.4 nm. From these analyses, the trap state density per unit area N_t under this laser condition is estimated to be $5.4 \times 10^{12}\,\mathrm{cm}^{-2}$. Further increases in the laser energy density continuously decreases the trap state density per unit volume N_t/L below the donor concentration N_D, and the barrier height E_b starts to decrease, as shown in Fig. 5(c). As a result, both the carrier concentration n and the carrier mobility μ are increased. The reduction in trap state density continues until the microcrystallization threshold. Microcrystallization causes N_t/L to increase again and both the carrier concentration and mobility decrease abruptly.

According to the model discussed above, the results in Fig. 4 can be understood that the trap state density also changes depending on the number of laser shots. As the number of laser shots is increased from one to five, the carrier mobility is decreased along with decreasing trap state density because the potential barrier height is increased. Since further increases in the number of laser shots from five to ten continuously decreases the trap state density, the carrier mobility is increased along with this. From these results, it is confirmed that not only the laser energy density but also the number of laser shots changes the trap state density. This is consistent with our previous analysis.[5]

5. Summary

The electrical properties of excimer-laser-crystallized lightly phosphorus-doped poly-Si films were examined. The electrical conductivity of the films changed from 6.0×10^{-7} to $2.3 \times 10^{-1}\,\mathrm{S/cm}$ as the laser energy density increased from 235 to $436\,\mathrm{mJ/cm}^2$ because the carrier concentration changed from 1.0×10^{11} to $1.8 \times 10^{17}\,\mathrm{cm}^{-3}$ along with the increasing laser energy density. The carrier mobility was $37.3\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$ at the laser energy density of $235\,\mathrm{mJ/cm}^2$, which decreased to $0.24\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$ when the laser energy density was $315\,\mathrm{mJ/cm}^2$, and then increased to $8.7\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$ at $436\,\mathrm{mJ/cm}^2$. These results can be explained in terms of carrier trapping by the localized trap states at the grain boundary and the reduction of the trap state density with increasing laser energy density. Since the carrier mobility shows a minimum value when the trap state density is identical to the donor concentration, the trap state density per unit area is estimated to be $5.4 \times 10^{12}\,\mathrm{cm}^{-2}$ when the laser energy density is $315\,\mathrm{mJ/cm}^2$ with five-shot irradiation.

The trap state density also changes along with the number of laser shots. By increasing the number of shots, the trap state density can be reduced.

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