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Infrared semiconductor laser irradiation used for crystallization of silicon thin films

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ABSTRACT

We report the rapid thermal crystallization of silicon films using infrared semiconductor laser. Carbon films were used on silicon films to absorb the laser light. Uniform crystalline regions were achieved by a line shape laser beam with a length of 20 μm. Polycrystalline silicon thin film transistors were fabricated in crystallized regions. The effective electron carrier mobility and threshold voltage were achieved to be 130 cm^2/Vs and 0.4 V, respectively, when the crystalline volume ratio of the silicon films was 0.95.

1. Introduction

Polycrystalline silicon thin film transistors (poly-Si TFTs) have been widely applied to switching and driving circuits for the flat panel displays [1,2]. Laser crystallization processes using pulsed excimer lasers have been widely used for the mass production of formation of poly-Si films at a low processing temperature because laser-induced rapid and local heating achieve crystallization of silicon films with a low heating energy [3,4]. However, there are serious problems of a low lasing emitting efficiency of 1%, low gas lifetime, and high running costs in operation of pulsed excimer laser. In order to overcome those problems, many rapid heating methods have been developed [5–7]. We have recently proposed a method of laser crystallization using an infrared semiconductor laser with black carbon films as photo absorption layers [8,9]. Black carbon films effectively absorb infrared laser light and are heated themselves. They have very high melting and evaporating points. Heating energy therefore effectively propagates from solid carbon films to the underlying silicon films.

In this paper, we report a rapid heating system on the order of ten microseconds with a line-shaped semiconductor laser beam achieved by optics and a mechanics of sample movement. We report laser crystallization conditions and crystalline properties including spatial uniformity. We also demonstrate the fabrication of n-channel poly-Si TFTs in the crystallized regions.

2. Experimental

Fig. 1 shows a schematic apparatus of the present laser irradiation system for crystallization for silicon films. The samples were mounted on an *X*–*Y* movable stage for irradiating laser over a large area. The stage was driven by a linear motor with a velocity of 1.5 m/s at most in the *Y* direction. The laser well time was controlled by changing the velocity of the stage in the *Y* direction. The sample was stepwisely moved with a pitch of 100 μm in the *X* direction by another liner stage each scanning in the *Y* direction. The samples were irradiated with 976 nm infrared semiconductor laser during the sample's movement. The optics were developed giving a line shaped beam with a length of 20 μm and a width of 500 μm. 40-nm-thick undoped hydrogenated amorphous silicon (a-Si:H) films were formed on quartz glass substrates by plasma enhanced chemical vapor deposition (PECVD). 200-nm-thick carbon films were subsequently formed on the a-Si:H films using the sputtering method.

Fig. 2 shows optical absorbance spectra for samples of simple 40-nm-thick a-Si:H film formed on quartz glass substrate and 200-nm-thick carbon formed on underlying 40-nm-thick a-Si:H film formed on quartz glass substrate. Although the 40-nm-thick a-Si:H film had a negligible small optical absorbance at 976 nm, there was a high optical absorbance of 78% when the carbon film was formed. It is suitable for laser heating with infrared semiconductor laser. After laser irradiation, carbon films were removed by oxygen plasma treatment. Raman scattering measurement was carried out to investigate crystalline states of laser annealed regions. The crystalline volume ratio was analyzed from the experimental spectra with three Gaussian component areas whose peaks were located at around 480, 500, and 515 cm^{-1} associated with transverse optical (*TO*) phonons for amorphous, nano-crystallline and crystalline structures, respectively [10].

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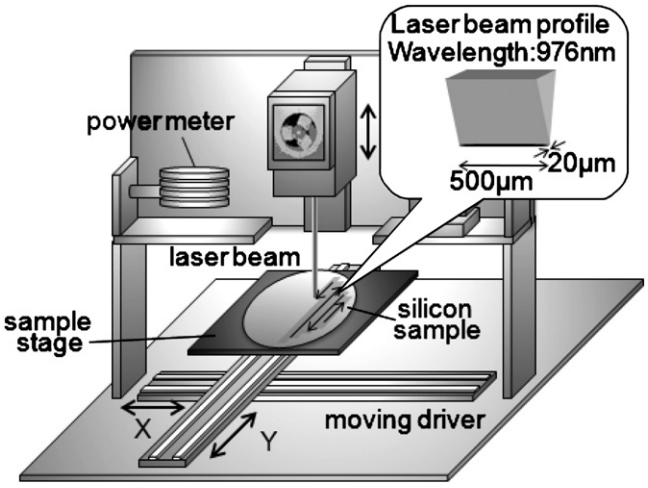

Fig. 1. Schematic apparatus of laser irradiation for crystallization of silicon films.

Poly-Si TFTs were fabricated in the laser annealed regions [11]. Phosphorus doped a-Si:H films with a thickness of 40 nm were first formed on glass substrate using PECVD. The doped films were removed at a channel region with a length of 100 μm and width of 100 μm by etching. They were used as dopant sources for forming source and drain regions. 30-nm-thick undoped a-Si:H films were deposited using PECVD over the whole area. The samples were heated at 430 °C for 1 h to release hydrogen atoms from the silicon layers. 200-nm-thick carbon films were subsequently formed on the a-Si:H films using the sputtering method. The samples were irradiated with infrared semiconductor laser. After laser irradiation, the carbon films were removed by oxygen plasma treatment. 100-nm-thick SiO_x films were deposited at room temperature on the silicon surface by the vacuum evaporation of SiO powders at a base pressure of 4×10^{-4} Pa. Contact holes were opened in the SiO_x films on the source and drain regions. Gate, source and drain electrodes were formed with Al metal. After TFT fabrication, samples were heated at 260 °C with 1.3×10^{6} Pa H_2O vapor for 6 h for defect reduction in SiO_x as well as SiO_x/Si interfaces [12,13].

3. Results

Fig. 3 shows Raman scattering spectra of 40-nm-thick silicon films irradiated for different laser dwell times ranging from 17 to 25 μs with a constant pitch in the *X* direction of 100 μm and a laser power of 40 W. The crystalline silicon phonon peaks were observed around wavenumber of 515 cm^{-1} irradiated for 17 μs. The silicon films were crystallized by heat diffusion from the top carbon film heated by laser irradiation. CVR was 0.43. The peak of crystalline silicon increased and the peak of a-Si:H around wavenumber of 480 cm^{-1} decreased as the laser dwell time increased from 17 to 25 μs. CVR increased to 0.95 in the case of laser irradiation for 25 μs.

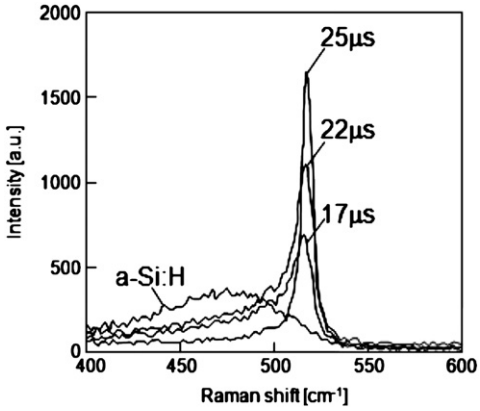

Fig. 3. Raman scattering spectra of 40-nm-thick silicon films irradiated for different dwell times ranging from 17 to 25 μs with a constant pitch in the X direction of 100 μm and a laser power of 40 W.

Fig. 4 shows CVR distribution in the normal direction (*X* direction) to laser scanning (*Y* direction) in the cases of irradiated different dwell times from 20 to 25 μs at 40 W. The averages of CVR were 0.44 and 0.48, respectively in the cases of laser dwell times of 20 and 22 μs. It markedly increased to 0.95 for the dwell time of 25 μs. Fig. 5 shows a photograph obtained by measurement of the bright field transmission electron microscope of sample in the case of laser dwell time of 25 μs. The silicon film was well crystallized with grain size ranging 0.2 to 1 μm.

Fig. 6 shows output (a) and transfer (b) characteristics of the n-channel poly-Si TFTs with a channel length and width of 100 μm in the case of laser irradiation for 20 μs and a laser power of 40 W. The CVR of channel region was 0.45. Output characteristics showed good ohmic characteristics. But there was a rather low drain current 2.8×10^{-8} A even by the gate voltage application of 6 V. The low CVR probably limited a carrier path low because of the poor crystalline state and resulted in rather low carrier mobility. The transfer characteristic showed a high threshold voltage at about 4 V.

Fig. 7 shows output (a) and transfer (b) characteristics of the n-channel poly-Si TFTs with a channel length and width of 100 μm in the case of laser irradiation for 25 μs and a laser power of 40 W. The CVR of channel region was 0.95. Output characteristics showed good ohmic characteristics. A high drain current of 8.8×10^{-5} A was

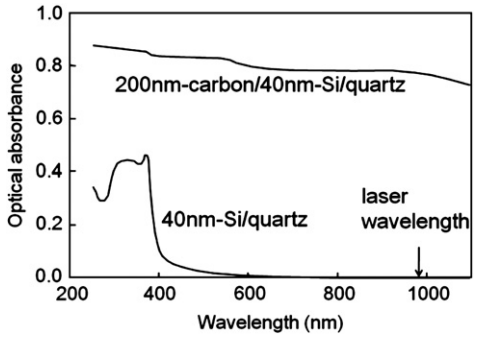

Fig. 2. Optical absorbance spectra for samples of a simple 40-nm-thick a-Si:H film formed on quartz glass substrate and 200-nm-thick carbon formed on underlying 40-nm-thick a-Si:H film formed on quartz glass substrate.

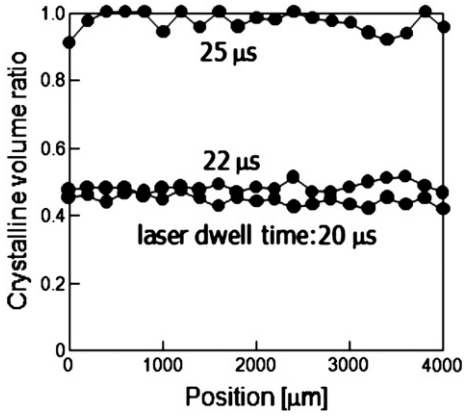

Fig. 4. CVR distribution in the normal direction of laser scanning at 40 W and with different dwell times from 20 to 25 μs.

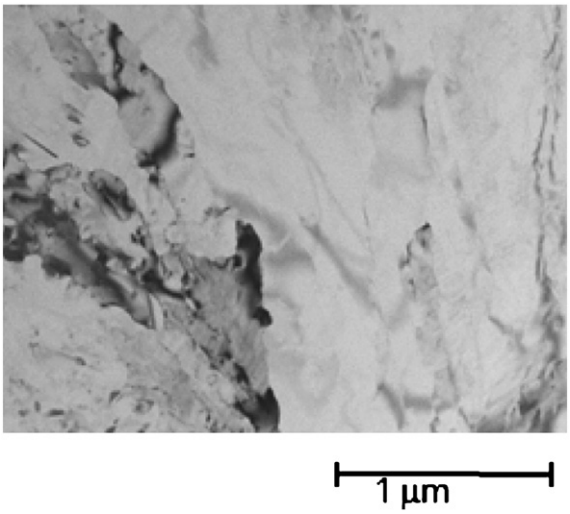

Fig. 5. Photograph obtained by measurement of the bright field transmission electron microscope of sample in the case of laser dwell time of 25 μs.

observed in the cases of a gate voltage of 6 V and a drain voltage of 10 V. The high CVR allowed a good carrier channel path at the SiO_2/Si interface. The transfer characteristic showed a low threshold voltage at about 1 V. The gate capacitance obtained by high frequency capacitance response as a function of a bias voltage for a metal oxide semiconductor structure resulted in an effective carrier mobility of 130 cm^2/Vs from the results of Fig. 7.

4. Discussion

The results of Raman scattering spectra and TEM observation revealed that silicon thin films were rapidly crystallized by the present method of infrared laser heating with carbon optical absorption layers. Crystalline properties strongly depended on laser dwell time.

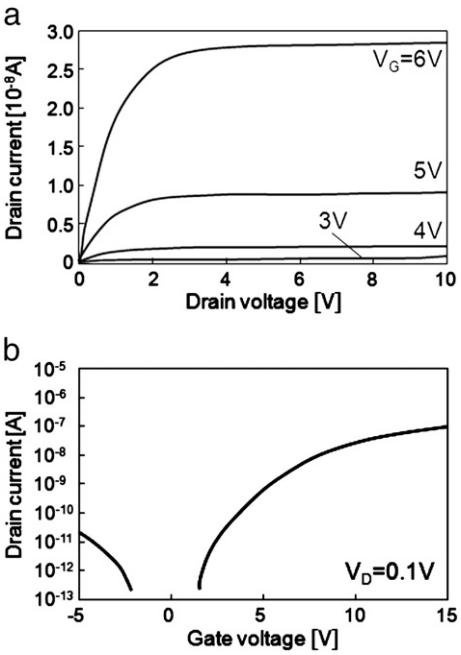

Fig. 6. Output (a) and transfer (b) characteristics of the n-channel poly-Si TFTs with a channel length and width of 100 μm in the case of laser irradiation for 20 μs and a laser power of 40 W.

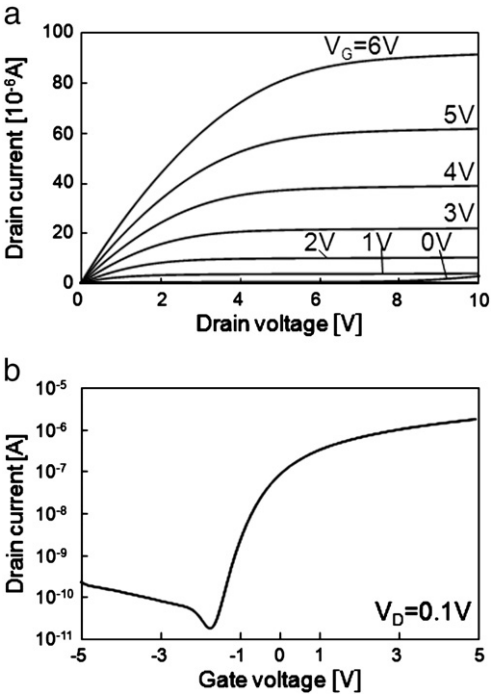

Fig. 7. Output (a) and transfer (b) characteristics of the n-channel poly-Si TFTs with a channel length and width of 100 μm in the case of laser irradiation for 25 μs and a laser power of 40 W.

When the laser dwell time was short of 20 and 22 μs, CVR was lower than 0.5. We believe that silicon films were crystallized in the solid state during laser irradiation. Short laser irradiation would not have given high enough energy to melt silicon films because silicon had a high latent heat [14]. A high CVR of almost 1 and large crystalline grains were observed in the case of laser irradiation for 25 μs. The silicon films were probably melted and crystallized well by heat diffusion from the top carbon film heated by laser irradiation. Needle-like shape crystalline grain was observed by TEM measurement, as shown in Fig. 5. This indicates lateral grain growth occurred along laser scanning direction. It is interesting that the film surface kept smooth. It will be an advantage for fabrication of TFT. Uniform CVR distribution means that 100-μm-overlapping irradiation was enough for formation of uniform crystallized films. A high threshold voltage of 4 V and low drain currents were observed for transfer characteristic of the n-channel poly-Si TFTs in the case of laser irradiation for 20 μs. The low CVR probably resulted in small crystalline grains and many grain boundaries associated with many charge trap defects states and carrier scattering sites in the channel region. They probably increased the threshold voltage and decreased the effective carrier mobility. A high threshold voltage of 1 V and high drain currents were achieved in the case of laser irradiation for 25 μs. The high CVR of almost 1 and large crystalline grains probably decreased the density of defect states and carrier scattering sites. This laser heating condition therefore resulted in an effective carrier mobility of 130 cm^2/Vs. Those results of Figs. 3 to 7 indicate a capability of high quality polycrystalline formation by infrared laser heating.

5. Summary

We investigated rapid thermal crystallization of silicon films using infrared semiconductor laser with carbon films as photo absorption layer and its application to the fabrication of poly-Si TFTs. A line shape laser beam of 976 nm infrared semiconductor laser with a length of 20 μm and a width of 500 μm was developed in order to achieve rapid heating by moving samples to the laser beam. Samples with 200-nm-

thick carbon formed on 40-nm-thick a-Si:H films on quartz glass substrate had a high optical absorbance of 78% at 976 nm. Crystallization of silicon films was observed by laser irradiation at 40 W for 17 μs. CVR increased from 0.43 to 0.95 as the laser dwell time increased from 17 to 25 μs. Large crystalline grains with a size of about 1 μm were formed in the case of laser dwell time of 25 μs. Uniform crystalline regions were achieved at a standard deviation of 0.022 in CVR by 100-μm-overlapping irradiation. The poly-Si TFTs fabricated in crystallized region with a crystalline volume ratio of 0.95 had a threshold voltage of 1.0 V and a carrier mobility of 130 cm^2/Vs.

Acknowledgements

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