Pulsed Laser System with Variable Pulse Duration for Laser Annealing

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We have developed a unique Nd:YAG laser source for laser annealing, which can oscillate with variable pulse duration. The pulse duration is electrically varied by three Pockels cells arranged in series. These Pockels cells are synchronized with each other. With this setup, we have achieved a variable pulse duration of 80-1300 ns by controlling the trigger timings and the applied voltages for each of the Pockels cells. In this report, the configuration of the laser source and the Q-switch control sequence are described. Moreover, qualitative annealing results obtained with the system are shown.

Key Words: Variable pulse-duration oscillation, Q-switch control, Nd:YAG laser, Laser annealing

1. Introduction

One of the techniques for yielding poly-silicon (poly-Si) thin film on a glass substrate is laser annealing, which is the melting of amorphous-silicon (a-Si) that is then re-crystallized into poly-Si with laser irradiation. This technique improves the electric characteristics of thin-film transistors (TFTs), especially the electric conductivity between the drain and source channels. The electric conductivity of the TFTs depends on the grain size; the existence of grain boundaries across the TFT channel inhibits electric current. Therefore, the grain size must be longer than the TFT channel and the direction of lateral growth must be along the direction of current in the TFT.

Grain growth is affected by the behavior of the surface temperature such as the increasing or decreasing rate of the temperature; in particular, the rate of decrease of the temperature around the melting point is important. Therefore, pulse duration is one of the most important factors for controlling grain growth in addition to the pulse energy and shift-shot pitch in a sequential lateral solidification (SLS) process. With regard to control of the pulse energy and shift-shot pitch, there have been many reports involving studies with excimer lasers. However, there have been fewer reports with regard to the effects of pulse duration, due to the lack of a laser with an electrically controllable pulse duration. In a previous report, the laser pulse duration has been increased by using a Pulse duration extender (PDE). Due to the long length of the required optical path and the large number of bending mirrors in the PDE, it cannot easily vary the pulse duration continuously.

To improve these disadvantages and to study the effect of pulse duration, we have developed a variable pulse-duration laser system using Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG) lasers. In this report, the configuration of the laser and Q-switch control sequence are described. Moreover, quantitative annealing results obtained with the system are shown.

2. Apparatus and Performances

2.1 Design of the 1064-nm Laser Cavity

To design a variable pulse-duration laser, we employed an ordinary Q-Switched Nd:YAG laser. The configurations of the laser cavity used are shown in Fig.1. We used a 1.1% Nd-doped YAG rod crystal (Laser Materials, Co., diameter = 5 mm, length = 100 mm) and a Xe arc flash lamp (Heraeus) to pump the Nd:YAG rod in the cavity. The Q-switch

Fig. 1 Schematic representation of the developed laser cavity. RM: rear mirror (R ≥ 99.8%); FM: front output mirror (R ≤ 8% Gaussian mirror); PC1-3: Pockels cells; qWP: quarter-waveplate; P1 and P2: polarizers; R1-5: resistors; PS1-3: stabilized power supplies; and SW1-5: high-voltage transistor switches. The trigger timing of the switches was controlled by trigger signals together with the Xe flash lamp for Nd:YAG excitation. The capacitance of the PC is about 6 pF, and the resistance can be varied from 1.5 to 17 kΩ.
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The system consists of a plate polarizer (P1, Lambda Research Optics, Inc.), a quarter-waveplate, and three Pockels cells (Gooch & Housego). These Pockels cells are electrically isolated in order to not to interfere with each other. The front and rear mirrors (FM, RM) reflect λ = 1064 nm light with R ≤ 8% (Gaussian mirror) and R ≥ 99.8%, respectively. The fluorescence life-time of the Nd:YAG rod is typically 240 μs, and the pumping lamp was flashed for a duration of 300 μs to accommodate the fluorescent life-time. The Nd: YAG rod accumulates optical energy while it is pumped by the flash lamp. Opening the Q-switch just after the pumping, almost all the energy in the rod is drawn out from the output mirror as a laser pulse.

To verify the shape of the laser pulse generated from the laser cavity, first, we operated only a single Pockels cell (PC1) in used to a non-inductive resistor (R1) and a high-voltage transistor switch (SW1). In this case, the voltage applied to the Pockels cell is described as follows:

\[ V_{ap} = V_0 \left( 1 - \exp \left( -\frac{t}{CR} \right) \right) \]  

where \( V_0 \) is the initial voltage, \( C \) is the capacitance of the Pockels cell (≈ 6 pF), and \( R \) is the resistance of the circuit.

The applied voltage follows an exponential drop-off with a time constant \( \tau = RC \). We can easily change the time constant by replacing the resistor with one of other value. In this case, the laser cavity generates a series of short discrete peaks, which decay exponentially (as shown in Fig. 2 (b)). Moreover, even if the time constant were changed by substituting a different resistor, the desired shape of the long pulse could not be obtained because the applied voltage decreases exponentially with time (Figs. 2 (a) and (b)). The ideal long-duration pulse for laser annealing would have a rectangular temporal waveform with a constant peak power. Therefore, it is difficult to generate the desired pulse by using a single switch and a resistor.

Next, to generate the desired shape of the long pulse, we added a second high-voltage transistor switch (SW2) and resistor (R2) in addition to SW1 and R1. Turning on the second switch around the time that the first peak ends, the time constant changed from \( R_1 \times C \) to \( (R_1 \times R_2 \times C) / (R_1 + R_2) \) instantly; by tuning on the second switch, the Q-switch was opened further. Then the short discrete peak after the first

Fig. 2 Voltages applied to Pockels cells and the corresponding pulse shape generated from the laser cavity. (a) and (b) Applied voltages driving only PC1 and the resulting pulse shapes. (c) and (d) Voltages sequentially applied to PCs and the resulting pulse shapes.
peak could be combined with the end of the first peak, in this way, we obtained a duration-expanded pulse (see Figs. 2 (c) "voltage2" and (d) "laser pulse2"). To combine more peaks to form a long-duration pulse, we tried to attach more switches and resistors in the same circuit. However, we could not drive more than three high-voltage switches in the circuit because the switches electrically interfere with each other. Therefore, additional Pockels cells that are electrically isolated are set up to provide further Q-switching of the laser in this paper (as shown in Fig. 1).

To further test the above scheme by including a third switch (SW3) and resistor (R3), we have obtained about a 350 ns-duration pulse from the laser cavity (Fig. 2 (d) "laser pulse3"). The laser pulse was generated by "voltage3" in Fig. 2 (c). The operating parameters of "voltage3" are as follows: the trigger timings of SW1-3 are 0, 600, and 750 ns, the initial voltages are -1.55, -1.14, and -0.39 kV, and the time constants are 1.09, 4.54, and 3.22 μs, respectively. Under these conditions, short discrete peaks were combined together, and as a result, a long duration pulse was generated as shown. By using additional switches (SW4, 5) and resistors (R4, 5), the output pulse duration from the laser source can be varied from 80 to 1300 ns. Under these long-pulse conditions, we have observed a constant pulse energy of about 80 mJ from the cavity; however, this is not enough to anneal. Therefore, we have installed optical amplifiers after the cavity.

2.2 Configuration of Laser Source for Annealing

To increase the pulse energy for laser annealing, two stages of optical amplifiers are used. Figure 4 shows the configuration of the 1064 nm laser source for annealing. We also used 1.1% Nd-doped YAG rod crystals in the optical amplifier (diameter = 9 mm, length = 120 mm), and both rods were pumped by a Xe arc flash lamp. Using the optical amplifier, the output pulse energy from the laser source system was amplified to a final pulse energy of 850 mJ, which was enough to anneal with the following projection optics. While the output pulse energy could be increased with the amplifier, parasitic oscillation occurred between the cavity and amplifier. To suppress the parasitic oscillation, we used a Faraday isolator (ISO; Electro-Optics Technology, Inc.) between the cavity and optical amplifiers.

Any fluctuation in a pulse emitted from the cavity is enhanced by the amplifiers (Fig.4(a)). The output pulse from the amplifiers fluctuates with a period of 50-80 ns. To smooth the output pulse, a 10-m delay line was set up after the amplifiers. The 10-m delay line causes a 33.3-ns time delay, which corresponds to half of the fluctuating period. The delay line divides an amplified pulse into two pulses by using a partially reflecting mirror (PM; R = 30%). The reflected pulse is again coupled with a 33.3-ns-delayed transmitted pulse at PM (Fig. 4(c)). The long 1064-nm pulse is combined with a 532-nm pulse at dichroic mirror (DM). The 532-nm pulse is used to melt an a-Si layer because a-Si has high absorption at 532 nm. On the other hand, the 1064-nm pulse cannot be absorbed by a-Si, but it can be absorbed by melting silicon. Therefore, emission of the 1064-nm pulse must be almost at the same time as that of the 532-nm pulse. Namely, the 532-nm pulse works as the initiator of the annealing process, and the 1064-nm pulse supplies heat to grow poly-Si crystals with large grain sizes.

As a result, we have observed long 1064-nm pulses of variable duration combined with the short 532-nm pulses (as shown in Figs. 6 (a-h)). The typical output pulse energy of the 532-nm pulse is 390 mJ, and the 1064-nm pulse energy is 850 mJ. The 532-nm pulse duration is about 20 ns.

2.3 Projection Optics for Laser Annealing

The projection optics for laser annealing are shown in Fig. 5. The optics consist of a beam homogenizer system, a patterned mask (with an aperture size of 250 μm square), and a micro lens array (MLA) as a projection lens. The micro lens projects the mask pattern onto the glass substrate, and the
The magnification factor is 1/5. The number of lenses in the MLA is $18 \times 26 (= 468)$ with a $461 \mu m$ pitch. Therefore, 468 regions of dimensions $50 \times 50 \mu m$ can be annealed by a laser shot at the same time.

3. Results of 1-shot Laser Annealing with a Long-Duration Pulse

As a consequence, we have carried out 1-shot laser annealing with this system. Figure 6 shows the result of the annealing. We used Secco etching to clarify the grain boundaries. Then, to observe the poly-Si crystals in lateral growth, we used FE-SEM to capture the crystal images.

As a result, we have confirmed the qualitative annealing effect of the 1064-nm long-duration pulse. Our results suggest that pulse duration is one of the important factors for lateral growth in a-Si annealing (Figs. 6(b') and (f')). In future work, we will study the correlation between pulse duration and grain size in more detail.

4. Conclusion

A qualitative correlation between pulse duration and grain size of laterally grown poly-Si on a substrate has been confirmed. This correlation would be changed by the configuration or material of layers on a TFT substrate. It would be inconvenient for a PDE system based on an optical delay line to change the pulse duration flexibly. A laser system with variable duration control is necessary to determine the optimum condition for various TFT substrates. Thus, a laser system equipped with a unique pulse-duration control scheme would be useful for laser annealing. Also this laser system can be applied to not only experimental research, but also to mass production in industry, because the optimum condition for mass production of different TFT designs can be determined and used in the manufacturing process.

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