Multichannel Poly-Si Thin-Film Transistors Prepared by Excimer Laser Annealing With Channel Width Comparable or Smaller Than the Grain Size

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Abstract—This paper presents results on low-temperature ($< 500\text{ }^{\circ}\text{C}$) multichannel poly-Si thin-film transistors (TFTs) prepared by KrF excimer laser annealing with a channel width that is comparable to or smaller than the poly-Si grain size. The cross-sectional scanning electron microscope is used to measure the effective channel width, and TCAD software is used to simulate the electron density distribution in the channel region. It is found that the TFTs with ten 40-nm-wide multichannels have superior electrical characteristics, including a higher on/off current ratio ($> 10^7$), lower leakage current ($8.8 \times 10^{-14}\text{ A}$), less grain boundary defects density, and a better subthreshold swing (0.45 V/dec).

Index Terms—Polycrystalline silicon, thin-film transistor (TFT).

I. INTRODUCTION

RECENTLY, there has been much interest in low-temperature poly-Si (LTPS) thin-film transistors (TFTs) technology for active matrix liquid crystal display [1] and active matrix organic light-emitting diode [2] due to their high carrier mobility. It is expected that all functional components made of poly-Si TFTs can be integrated on a substrate for system-on-chip [3] and system-on-panel applications. However, owing to the existence of grain boundary defects in the channel region, the OFF-state leakage current and threshold voltage (V_{th}) of the poly-Si TFTs are relatively high, as compared with those of hydrogenated amorphous silicon (a-Si:H) TFTs [4].

Hence, it is very essential to minimize the grain boundary defects in order to improve the electrical characteristics of poly-Si TFTs. It has been reported that the poly-Si TFTs with several multichannels can effectively reduce the grain boundary defects [5]–[7]. Moreover, the TFT characteristics are dramatically improved with a reduced channel width, particularly when the channel width is close to the grain size [8], [9]. Therefore, the relation between the grain size and the channel width is a critical issue when the device dimension is scaled down.

This paper will present the results of poly-Si TFTs when the channel width is smaller than the grain size. The amorphous sil-

Fig. 1. Schematic diagram showing the device structure of a low-temperature ten 40-nm-wide channel poly-Si TFT prepared by KrF excimer laser annealing.

icon deposited by plasma-enhanced chemical vapor deposition (PECVD) is first annealed at $500\text{ }^{\circ}\text{C}$ for 10 min in order to drive out the hydrogen atoms and then irradiated by KrF excimer laser in order to form a polycrystalline grain with an average size of $\sim 200\text{ nm}$. Single-, double-, and ten-channel poly-Si TFTs, with a channel width that is comparable to (400 and 200 nm) or smaller (40 nm) than the grain size (200 nm), are fabricated, and their electrical characteristics are investigated. Unlike the double gate FinFET with a 17-nm-thick gate insulator [10], the 100-nm-thick PECVD SiO_x is used here. Hence, the cross-sectional scanning electron microscope (SEM) is used to measure the total effective channel width, and the TCAD simulator is used to simulate the electron density distribution in the channel region. Finally, the performance of TFTs, including its electrical characteristics, V_{th} , I_{min} , on/off current ratio, mobility, and grain boundary defects, are compared.

II. EXPERIMENTS

Fig. 1 shows the schematic diagram of this process. First, 50-nm-thick intrinsic a-Si:H and 20-nm-thick n-type phosphorus-doped a-Si:H layers are deposited by PECVD on oxidized Si substrate. During deposition, the substrate temperature, RF power density, and chamber pressure are fixed at $250\text{ }^{\circ}\text{C}$, 0.11 W/cm^2 , and 0.45 torr, respectively. As for the gas flow rate, the undoped a-Si:H layer is $3(\text{H}_2)$ and $3(\text{SiH}_4)$ sccm, and the n-type doped a-Si:H layer is $2(\text{H}_2)$, $3(\text{SiH}_4)$, and $1(3\% \text{ PH}_3 \text{ in } \text{H}_2)$ sccm with a $[\text{PH}_3]$ to $[\text{PH}_3 + \text{H}_2 + \text{SiH}_4]$ gas ratio of 5000 ppm. Second, the n-type a-Si:H layer is patterned and etched by reactive-ion etching (RIE) to define the channel region of the TFT. Following that, the sample is sent to a furnace for 10 min at $500\text{ }^{\circ}\text{C}$ under a nitrogen environment

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TABLE I
DEVICE DIMENSIONS OF E1, E2, AND E3 POLY-Si TFTs

Device Name	Channel length (μm)	W_1 (nm)	W_2 (nm)	Channel Number	Total Effective Channel Width (nm)
E1	5	400	55.9	1	512
E2	5	200	57.7	2	631
E3	5	40	75.3	10	1905

(a)

(b)

Fig. 2. (a) SEM photograph of poly-Si grain prepared KrF excimer laser annealing after Secco etching. The average grain size is 200 nm. (b) SEM image of the E3 device at the channel region. The inset is an enlargement of one 40-nm-wide channel.

in order to expel hydrogen. After irradiating by excimer laser (KrF, the pulse duration time is 28 ns, 330 mJ/cm^2) at room temperature, multiple nanoscaled channels are patterned by electron beam lithography and transferred by RIE. A 100-nm-thick SiO_x is subsequently deposited by PECVD at 250°C as a gate insulator. After opening the contact windows for source and drain, the sample is treated by NH_3 plasma at 250°C for 3 h, with a pressure of 2 torr and an RF power density of 0.44 W/cm^2 . Finally, 150-nm-thick aluminum is evaporated on the devices to form ohmic contact and gate/source/drain electrodes. The postmetal annealing condition is 5 min at 400°C under a nitrogen environment.

The current–voltage (I – V) characteristics of fabricated devices are measured by an HP 4156 semiconductor parameter analyzer.

Fig. 3. Cross-sectional SEM image of the (a) E1, (b) E2, and (c) E3 devices along the AA' direction in Fig. 1.

III. RESULTS AND DISCUSSION

In this paper, TFTs are divided into three groups based on their channel number and width, i.e., 400-nm single channel (E1), 200-nm dual channel (E2), and ten 40-nm multichannel (E3), which are with the same channel length ($5 \mu\text{m}$), as listed in Table I.

Fig. 2(a) and (b) shows the SEM image of the poly-Si channel layer before and after patterning the channel. In Fig. 2(a), after excimer laser annealing and Secco etching, the poly-Si grains with very clear boundaries are observed. The average grain size is about 200 nm. Fig. 2(b) shows the SEM image of the channel region of the E3 device. Each channel in the E3 device is 40 nm wide, and the distance between each neighboring channel is $1 \mu\text{m}$. The inset of Fig. 2(b) is the enlargement of one 40-nm-wide poly-Si channel.

Fig. 3(a)–(c) shows, respectively, the cross-sectional SEM images of the E1, E2, and E3 devices along the AA' direction in Fig. 1. It is obvious that the poly-Si channel region is trapezoidal in shape. Moreover, due to the 100-nm-thick SiO_x ,

Fig. 4. Electron density distribution of the (a) E1 and (b) E3 devices. The voltage applied in the simulation is $V_{GS} = 5$ V and $V_{DS} = 0.1$ V.

the cross section of these devices are different from that of the double gate FinFETs [10].

Fig. 4(a) and (b) shows the electron density distribution of the E1 and E3 devices by using the TCAD simulator. The construction of the simulation models is based on the cross-sectional SEM images in Fig. 3(a) and (c). The trap model of the grain boundary in our simulation is based on the method of Levinson *et al.* [11]. Considering that the poly-Si grain size is about 200 nm, it is assumed that there is one grain boundary in E1 (the channel width is twice that of the grain size) and there is no grain boundary in E3 (the channel width is smaller than the grain size) along the AA' direction. Apparently, the electron density on the top side (W_1) of the channel is very much the same as that on the two sidewalls (W_2). Hence, these two devices are effectively under trigate control. The sidewall conduction width (W_2) in Fig. 3, then, must be counted into the total effective channel width. Accordingly, the total effective channel width is $(W_1 + 2W_2)$ times the channel number. As a result, the effective channel widths of E1, E2, and E3 devices are 512, 631, and 1905 nm, respectively.

In order to examine the effect of multichannel and narrow channel widths, the electrical characteristics of the three kinds of TFTs are compared. Fig. 5 shows the normalized transfer curve of the E1, E2, and E3 devices. It is clear that the on current of the E3 device at the gate bias $V_{GS} = 5.3$ V and the drain bias $V_{DS} = 1$ V is approximately 20%–25% higher than those of the other two devices. Additionally, the leakage current of the E3 device is reduced about two orders of magnitude compared with those of the E1 and E2 devices. Therefore, the E3 devices have a higher on/off current ratio ($> 10^7$) than the others.

Fig. 6 shows the normalized output characteristics of the E1, E2, and E3 devices. The applied gate voltage is 0–4 V. The drain

Fig. 5. Normalized transfer curves of LTPS TFTs with different width to length ratios ($W/L = 512/5, 631/5$, and $1905/5$ nm/ μ m).

Fig. 6. Comparison of normalized I_D - V_D curve of LTPS TFTs with different width to length ratios ($W/L = 512/5, 631/5$, and $1905/5$ nm/ μ m).

current I_{DS} of the E3 device at the gate bias $V_{GS} = 4$ V and drain bias $V_{DS} = 4$ V is 16% higher than that of the E1 device and 10% higher than that of the E2 devices.

Fig. 7 shows the plots of (left) the TFTs' minimum leakage current and the (right) maximum on/off current ratio of the E1, E2, and E3 devices. The minimum leakage current is defined as the minimum drain current I_{DS} at the drain bias $V_{DS} = 0.1$ V. The maximum on/off current ratio is defined as $V_{DS} = 1$ V. As can be seen, the leakage current is almost the same for both E1 and E2 devices. However, the minimum leakage current of E3 decreases to one order of magnitude compared with the other two devices. It is because the E3 TFTs have a multichannel structure, which results in a larger surface area passivated by NH_3 plasma. In addition, the plasma treatment can further reduce the number of grain boundary defects and lead to low leakage current [12], [13]. Moreover, the maximum on/off current ratio rises with the increase of the channel number. It can be explained that the E3 TFT structure has a better trigate control capability.

The statistical distributions of the threshold voltage and field effect mobility for three different devices are shown in Fig. 8. The mobility is obtained from the maximum transconductance at a low drain voltage $V_{DS} = 0.1$ V. The threshold voltage is

Fig. 7. Minimum leakage current and maximum on/off current ratio of the E1, E2, and E3 devices.

Fig. 8. Statistics of threshold voltage (V_{th}) and field effect mobility (μ) of the E1, E2, and E3 devices.

defined as the gate bias for a normalized drain current of $I_{DS} \times L/W = 10^{-8}$ A at $V_{DS} = 0.1$ V. The threshold voltage of three poly-Si TFTs with a single channel (E1) and double (E2) and ten (E3) channels fabricated by ELA are $3.1(\pm 0.3)$, $2.9(\pm 0.4)$, and $2.6(\pm 1.4)$ V, respectively. Moreover, the mobility of three poly-Si TFTs with a single channel (E1) and double (E2) and ten (E3) channels fabricated by ELA are $17(\pm 3)$, $18(\pm 3)$, and $26(\pm 8)$ $\text{cm}^2/\text{V} \cdot \text{s}$, respectively. Clearly, the variations of the V_{th} and mobility increase with the increasing channel number and decreasing channel dimension. The explanation may be that when the channel width is smaller than the grain size of the poly-Si, the number of grain boundaries in the channel is not uniform, which will affect the uniformity of the electrical characteristics [9], [14].

To investigate the effect of grain boundaries in the three kinds of LTPS TFTs, the grain boundary trap-state densities (N_{trap}) are estimated by the method of Levinson *et al.* [11]. The relationship between I_{DS} and V_{DS} is written as follows in the linear region:

$$I_{DS} = (W/L)C_{OX}V_{DS}V_G\mu_g \times \exp(-q^3 N_{trap}^2 d / 8KT\epsilon_S C_{OX} V_G)$$

where C_{OX} is the gate oxide capacitance per unit area, μ_g is the carrier mobility at the Si grain boundary, ϵ_S is the dielectric

Fig. 9. Plot of $\ln(I_{DS}/V_G)$ versus $(1/V_G)$ for E1, E2, and E3 low temperature poly-Si TFTs.

constant for Si, and d is the thickness of the induced channel in the poly-Si.

Therefore, the N_{trap} is extracted from the slopes of $\ln(I_{DS}/V_G)$ versus $1/V_G$ at $V_{DS} = 0.1$ V and high V_G . It is shown in Fig. 9 that the E3 device exhibits an N_{trap} of $6.9 \times 10^{11}/\text{cm}^2$, which is 1.1 times smaller than that of the E1 and E2 devices, i.e., $\sim 7.4 \times 10^{11}/\text{cm}^2$. This result implies that the E3 TFTs, with ten 40-nm-wide channels, possess fewer grain boundary defects density, which are also supported by the lower V_{th} and less leakage current.

IV. CONCLUSION

In conclusion, the LTPS TFTs prepared by KrF excimer laser annealing with multiple channels have been successfully fabricated. The trigate structure is confirmed by cross-sectional SEM. The TFTs with ten channels exhibit better electrical performance than those with single and dual channels, i.e., a higher on/off current ratio ($> 10^7$), lower leakage current (8.8×10^{-14} A), minimum grain boundary defects density ($6.9 \times 10^{11} \text{ cm}^{-2}$), and a better subthreshold swing (0.45 V/dec). It is found that when the channel width is smaller than the poly-Si grain size, the uniformity of the mobility and threshold voltage degrades.

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