Single-Grain Si TFTs Fabricated on a Precursor from Doctor-Blade Coated Liquid-Si

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Printing is attractive for manufacturing flexible circuits. This manuscript presents our investigation of single-grain Si TFTs fabricated from printed liquid-Si, on a polyimide substrate with the maximum process temperature of 350 °C. The field-effect mobility is 460 cm²/Vs for electrons and 121 cm²/Vs for the holes. CMOS inverters were also fabricated. The devices function at the bending diameter of 3 mm. The device performance under the bending stress was discussed.

Introduction

Flexible, wearable and disposable electronics attract a lot of attentions in recent years. [1]. The printing method, which is suitable for manufacturing flexible circuits, enables the low-cost fabrication on the flexible substrates. Several groups have presented their approach to the printed flexible TFTs and circuits, using organic semiconductors [2], and metal oxide semiconductors [3]. However the carrier mobilities and the device reliability of the above mentioned works are relatively low, comparing with the traditional IC fabrication using the crystalline Si, due to the limit of the semiconductor material. To fabricate Si devices with the printing process, a low-cost process due to the absence of vacuum and lithography and could be used for the flexible devices, Shimoda, et al., have reported the fabrication of poly-Si TFTs from spin-coated liquid-Si material, resulting in the carrier mobility of 108 cm²/Vs for electrons. [4] To improve the carrier mobility, our group has reported the approach of fabricating single-grain Si TFTs from spin-coated liquid Si, [5], on the single Si grains crystallized using the excimer laser with the μ -Czochralski process [6]. The devices were with the carrier mobility of 391 cm²/Vs and 111 cm²/Vs for electrons and holes, respectively. We have also developed the low-temperature fabrication of single-grain Si TFTs on the polyimide substrate from doctor-blade coated liquid-Si. [7]

In this paper, we would like to demonstrate the single-grain Si TFTs fabricated on a precursor from liquid-Si, and the substrate transfer process we applied to transfer the devices on a flexible plastic substrate. The flexibility and the response to the bending stress are investigated and shown.

Experiments

The same fabrication process is used as in our earlier publication, [7] as shown in Figure 1. First, narrow cavities with the width of 100 nm and the depth of 700 nm were made on top of the SiO₂ layer on the polyimide substrate. For the ease of handling the sample in the process, a c-Si wafer was used to support the polyimide substrate. Then pure

cyclopentasilane (CPS) was doctor-blade-coated on top of the SiO_2 surface. CPS is a photo-sensitive cyclo silicon-hydrogen compound and with a liquid-phase, which is referred as liquid-Si in our research. After the UV lamp irradiation to polymerize CPS to poly-silane, the sample was treated on a hotplate with 350°C in the inert gas atmosphere, to break the Si-H bond and to form the 3D Si network. After the treatment, the film became a-Si, as shown in the Raman Spectroscopy result in Figure 2. [7]

Figure 1 Schematic of single-grain Si TFT fabrication process on a precursor from liquid-Si on a polyimide substrate.

Figure 2 Raman spectroscopy of the a-Si film formed with the liquid-Si at 350°C . The c-Si peak is a signal of the substrate.

A dehydrogenation treatment was needed to avoid the film ablation due to the H_2 explosion in the laser crystallization during the μ -Czochralski process. The film was dehydrogenated using the XeCl excimer laser with a wavelength of 308 nm at room temperature. Figure 3 shows the Elastic Recoil Detection Analysis (ERDA) result, that after part of the dehydrogenation treatment, till the laser energy density of 500 mJ/cm^2 for the multi-shot method (Figure 3a) [7], the hydrogen concentration at the surface decreased.

After the multi-shot laser treatment, the crystallization of the Si film was performed with the μ -Czochralski process by the same excimer laser. The Si film was melt by the laser till a certain depth in the narrow cavity and during the solidification process, only one grain was filtered by the narrow cavity and a single Si grain was formed. The largest grain dimension was $3 \mu\text{m}$, as shown in the SEM image in Figure 4. [7]

Figure 3 ERDA result of (blue curve) the hydrogen concentration of the a-Si film after the dehydrogenation by the flash lamp, comparing with (red curve) that of the as-deposited film

Figure 4 SEM image of the crystallized grains at predetermined positions with a maximum diameter of 3 μm .

The top-gated single-grain Si TFTs were fabricated using the self-alignment method, as shown in Figure 2(e) and (f). [7] Considering the temperature limit of the polyimide substrate, the gate oxide was formed by the Inductively Coupled Plasma (ICP) oxide at 250 °C and the Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide by TEOS at 350 °C. The dopants in the source and the drain region were activated by the excimer laser at room temperature.

Figure 5 shows the transfer characteristics of the NMOS and the PMOS single-grain Si TFTs. The field effect mobility, calculated at a low drain voltage (0.02 V) in the linear region, was 460 cm^2/Vs and 121 cm^2/Vs for electrons and holes, respectively. The carrier mobility is much higher than that of the organic TFTs [2], the metal oxide TFTs [3], the a-Si TFTs [8] and the poly-TFTs [4] fabricated on flexible substrates. Figure 6 shows the output curve of a CMOS inverter, with a full swing of 5 V.

Figure 5 Transfer characteristics of NMOS TFTs before the peeling-off and after the transfer.

Figure 6 Output characteristic of CMOS inverter with the W/L ratio of 2 between PMOS and NMOS TFTs (red) before peeled off and (blue) after transfer

Substrate Transfer Process

In [7], we have reported a substrate transfer process to transfer the devices from the polyimide coated c-Si wafer to a flexible plastic PEN foil with the thickness of 125 μm , by etching off the polyimide substrate and detached with a blue dicing tape. After the transfer process, the carrier mobility of the same devices degraded to 310 cm^2/Vs and 110 cm^2/Vs for electrons and holes, respectively, as shown in the transistor transfer characteristics in Figure 5. After the transfer process, the CMOS inverter still shows a full swing of 5 V, but with a less-centred threshold voltage, shown in Figure 6.

The response of the bending stress of the NMOS and the PMOS transistors was tested by fixing the flexible devices on a cylinder, with the diameter down to 6 mm. (Figure 7(a)) [9] Figure 7(b) shows the normalized electron and hole mobility as a function of the bending diameter. [9]The devices were functioning until the bending diameter of 6 mm. The reason of the disfunction is mainly that the cracks in the SiO_2 underlayer caused by the bending broke the contact lines and the contact pads. Under the bending, the electron mobility degraded more than the hole mobility, because of the difference in the change of the energy band diagram due to the different shape of the conduction band and the valence band. [10]

Figure 7 (a) Photo of fixing the devices on a cylinder for the bending test, and (b) Normalized field effect mobilities as a function of the bending diameter

To reduce the mechanical stress to the device layer, another polyimide layer was added on top of the device layer. As illustrated in Figure 8, after the single-grain Si TFTs fabrication from spin-coated liquid-Si, a polyimide layer with the thickness of 10 μm was spin-coated on top of the devices. After that, contact holes were made to have access to the metal pads. Figure 9 is a photo of the flexible devices with the polyimide sandwiched structure. Because of the sandwiched structure, the mechanical stress neutral line was shifted to the device layer.

Figure 8 Illustration of the polyimide sandwiched structure

Figure 9 Photo of the flexible-devices with the polyimide sandwiched structure

Figure 10 shows normalized mobilities of the NMOS and the PMOS TFTs with the double polyimide sandwiched structures when they are flat and bent at the diameter of 10 mm, 6 mm and 3 mm, and after 10, 30 (for PMOS only), 50 (for NMOS only), 60 (for PMOS only), and 140 bending-release cycles with the bending diameter of 3 mm. Because of the minimized stress in the device layer, the cracking in the SiO₂ underlayer was restrained and the devices were functional at the bending diameter down to 3 mm, which is 50 % improved than the last method. The bending does not affect the device performance as much as the substrate transfer process. After 140 bending-release cycles with a bending diameter of 3 mm, the devices were still functioning. The main reason of the device failure would be the contact pad scratched-off after too many probing for the measurement.

Figure 10 Normalized field effect mobilities as a function of the bending diameter for the flexible devices with sandwiched structure, characterized when the devices were flat, bent at a bending diameter of 10 mm, 6 mm and 3 mm, and after 10, 30, 50, 60, 140 bending-release cycles at a bending diameter of 3 mm

Conclusion

In this paper, we have reported a fabrication approach for the single-grain Si TFTs on the precursor from liquid-Si on a polyimide substrate. The devices were fabricated with a maximum process temperature of 350 °C, with the carrier mobilities of 460 cm²/Vs and 121 cm²/Vs for electrons and holes, respectively. The devices were transferred to a flexible plastic foil and still function at the bending diameter of 3 mm.

Acknowledgments

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