A COMMON-GATE CMOS INVERTER WITH n -CHANNEL AMORPHOUS SILICON THIN-FILM TRANSISTOR FORMED ON A CRYSTALLINE PMOSFET

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Abstract—A common-gate complementary metal-oxide-semiconductor (CMOS) inverter consisting of an n -channel amorphous silicon (a-Si:H) thin-film transistor on top of 1.2 μm high Al gate of the crystalline silicon p -channel metal-oxide-semiconductor (PMOS) transistor has been achieved successfully. The success of this inverter demonstrates the feasibility of depositing 3500 Å thick amorphous silicon material on a surface with roughness in the order of 1.2 μm . It is found that growing an undoped amorphous silicon layer before the deposition of SiN_x insulator is necessary to avoid the permanent destruction of the underlying PMOS due to the stress imposed by the SiN_x . The vertical integration of crystalline silicon and amorphous silicon devices to form three-dimensional circuits is a promising technique for future applications in high density memory cell and neural network image sensors.

In the advance of ultra-large scaled integrated (ULSI) circuit technology, the size of the individual device has been shrunk continuously. One way to achieve this is to stack the load element on top of the transistor to form a three-dimensional (3D) architecture such as the integration of a thin film transistor (TFT) on top of the metal-oxide-semiconductor (MOS) field effect transistor in 4 Mb SRAM[1–3]. In addition, in the application of neural network image sensors[4], the amorphous edge detector can be grown directly on the crystalline silicon ULSI circuit, so that the detected edge signals can be processed by the underlying circuit in parallel. In this paper, we present the results on the successful integration of a common-gate complementary metal-oxide-semiconductor (CMOS) inverter which is composed of an amorphous silicon (a-Si:H) TFT on top of a 1.2 μm high Al gate of the crystalline silicon p -channel MOS (c-PMOS) transistor.

Figure 1(a) and (b) show the circuit diagram and cross section of the integrated PMOS transistor with an amorphous TFT (a-TFT) as the active driver. The fabrication processes are: the starting silicon wafer is a lightly doped n -type substrate. After the standard RCA cleaning process, the 7000 Å field oxide is grown. The first lithographic step is to pattern the source and drain regions, the field oxide on top of these regions is etched off using buffered oxide etch (BOE). Then a thin buffer oxide about 300 Å thick is grown, followed by source and drain implantation with BF_2^+ . The second step is to define the active region. The field oxide in this region is first stripped, then a 400 Å thick gate oxide is regrown. Its quality and uniformity are critical in determining the proper device characteristics. The next step is to open source and drain contact regions. The final step is to evapor-

ate and pattern Al metal followed by annealing at 350°C for 10 min so that the crystalline PMOS is completed. The gate length and width are 30 and 300 μm , respectively.

As for the fabrication processes for the upper a-TFT, the first step is the deposition of 200 nm Cr and patterned to cover the contact window area. This Cr serves as etching stop because the etching solution of a-Si:H will also attack underlying Al. Afterwards, a 200 nm thick a-Si:H i layer, 150 nm SiN_x , 200 nm a-Si:H i , and 50 nm n^+ layers are grown successively. The deposition conditions are the following: substrate temperature 250°C, chamber pressure 0.5 torr, RF frequency 10 MHz. The doping of n^+ layer is from 3600 ppm PH_3 . The first i layer is a buffer layer to separate gate oxide SiO_2 and SiN_x . It is found that if no buffer layer is inserted between these two materials, there will be a fatal destruction of the I - V characteristics of underlying c-PMOS due to the stress between SiO_2 and SiN_x . SiN_x is the gate insulator of the a-TFT. The second i layer serve as channel with the n^+ layer as the contact layer. Then the windows are opened to contact the underlying Cr. Finally the Al layer is evaporated and patterned and the n^+ a-Si:H layer is then etched away by reactive ion etching (RIE). This completes the entire fabrication process. The gate length and width are 20 and 280 μm , respectively.

In the integration of the PMOS and top amorphous TFT, a serious problem was encountered. When a 150 nm thick SiN_x is deposited directly onto the thin SiO_2 on top of the drain of the PMOS, the device properties of PMOS are seriously degraded. The common source I - V characteristics of a n -channel MOS (NMOS) before and after degradation were shown in Fig. 2(a) and (b). Before deposition of SiN_x ,

the NMOS behaves normally with a threshold voltage of -0.3 V. After deposition of SiN_x , a leakage path between n^+ source (drain) and p^- bulk region was apparently formed so that the NMOS cannot be turned off. This is due to the fact that if the bulk-source (drain) p - n junction periphery are not protected by the thick field oxide due to the misalignment in the photolithography process and undercut in the etching process, degradation will occur, which persists even when the SiN_x layer has been etched away. The problem may be due to the stress-induced interface states at the p - n junction periphery. This difficulty is removed by growing a 200 nm thick undoped a-Si:H layer before the deposition of SiN_x . Figure 2(c) shows the final I - V characteristics of the NMOS after adopting this new process, and no leakage current is observed. The merits of this new process are two-fold: firstly, it prevents the stress on the underlying SiO_2 . Secondly, the inserted i layer can serve as a protective layer to avoid the transient breakdown of the amorphous TFT. The reason is that under normal operation conditions, the buffer layer is a dielectric insulator. When there is a large voltage pulse applied to the gate, the i layer will absorb most part of the potential drop initially because it acts as a resistor in series with the SiN_x capacitor. This prevents the permanent breakdown of the SiN_x gate.

Fig. 1. (a) The circuit diagram and (b) cross section of the integrated common gate CMOS inverter consisting of a crystalline PMOS and amorphous TFT.

Figure 3(a) shows the common-source I - V characteristics of underlying PMOS with gate bias varying from -1 to -6 V. The maximum field-effect mobility in the saturation region is $39 \text{ cm}^2/\text{V}\cdot\text{s}$. The reason for the low field-effect mobility is probably that the nonself-align processes introduce a large source series resistance. Figure 3(b) shows the transfer I_D vs V_{GS} curve of this PMOS. The threshold voltage is -1.2 V and the transconductance at 1 mA is 1.5 mS/mm . Figure 4(a) shows the common source I - V characteristics of the top amorphous TFT with the gate bias as the independent parameter.

Fig. 2. (a) Original and (b) degraded I - V characteristics of crystalline NMOS before and after the deposition of SiN_x on SiO_2 , respectively. (c) The I - V characteristics of underlying NMOS after the insertion of amorphous layer between SiN_x and SiO_2 layer.

Figure 4(b) displays the transfer I_D vs V_{GS} plot of this a-TFT. The on-off ratio exceeds four orders of magnitude and the threshold voltage is 1.5 V. The field effect mobility obtained from the I_D vs V_{DS} plot is $0.23 \text{ cm}^2/\text{V}\cdot\text{s}$, which is typically of a-SiN_x gate TFT. The gate is shorted to the drain during the measurement. Figure 5 shows the transfer curve of this CMOS inverter. For gate voltage V_{GS} smaller than 2.7 V, the PMOS is on and TFT is off, so that the applied voltage 5 V is fed through the PMOS and appears at the output. When V_{GS} exceeds 2.7 V, PMOS is turned off, while the TFT is turned on. The output voltage is driving to below 0.2 V.

In conclusion, the integration of the common gate CMOS inverter which consists of an amorphous TFT directly grown on top of the crystalline PMOS

(a)

(b)

Fig. 3. (a) The common source I - V characteristics of PMOS in the integrated inverter. The gate bias V_G varies from -1 to -6 V. (b) The transfer I_D vs V_{GS} characteristics of c-PMOS in the integrated circuit. V_{DS} is fixed at -0.1 V.

(a)

(b)

Fig. 4. (a) The I - V characteristics of amorphous TFT in the integrated inverter. The gate bias V_{GS} varies from -3 to 5 V. (b) The transfer I_D vs V_{GS} characteristics of amorphous TFT in the integrated circuit. V_{DS} is fixed at 5 V.

Fig. 5. The transfer curve of the integrated CMOS inverter.

over $1.2\text{ }\mu\text{m}$ thick Al gate has been successfully achieved. Furthermore, a new technique by inserting a buffer *i* layer between SiO_2 and SiN_x layer is proposed to solve the stress problem and preserved the normal performance of the crystalline MOSFET.

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REFERENCES

1. A. O. Adan, K. Suzuki, H. Shibayama and R. Miyake, *IEEE Symp. on VLSI Technology*, pp. 19–20 (1990).
2. Y. Uemoto, E. Fujii, A. Nakamura and K. Senda, *IEEE Symp. on VLSI Technology*, pp. 21–22 (1990).
3. M. Kinugawa, M. Kakumu, T. Yoshida, T. Nakayama, S. Morita, K. Kubota, F. Matsuoka, H. Oyamatsu, K. Ochii and K. Macguchi, *IEEE Symp. on VLSI Technology*, p. 23 (1990).
4. W. J. Sah, S. C. Lee, H. K. Tasi and J. H. Chen, *Appl. Phys. Lett.* **56**, 2539 (1990).