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High-performance Transfer Printing method using Acetone Soluble Tape without adhesion promoter for Heterogeneous Integration

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Abstract

High-performance transfer printing method using a new soluble tape which can be dissolved in acetone can be used in heterogeneous integration. Si inks were transferred onto GaN/Sapphire substrates by this new method (AST) to compare with other methods. Results present AST has good performances. Various alien substrates, even curvilinear surfaces, can be selected as receiver substrates. Si TFTs on sapphire substrate were fabricated by AST. All the results confirm that AST is an effective method in heterogeneous integration.

1. Introduction

Integrating different materials on one single chip to fabricate different devices is a key means to increase the integration scale and functional diversity of chip [1]–[3]. Due to high temperature process existing in impurity activation and alloying annealing which are essential process steps in microelectronics industry, adhesion promoter which can't bear the high temperature shouldn't be coated on receiver substrates. Hence, transfer printing using PDMS by kinetic control of adhesion without adhesion promoter is developed and applied [4]. But there are two factors in this approach limiting its use: (1) the adhesion strength which depends on peeling velocity is difficult to control during "pick-up" and "printing"; (2) the adhesion switching ratio is too low to complete an effective transfer printing [5]. Then some efforts were reported including modifying the surface of PDMS to increase the adhesion switching ratio [6] and changing the operation method of transfer printing [7], [8]. These improvements were proved to be effective to increase the transfer printing efficiency. However, the method which is modifying the surface of PDMS is high-cost, complicated and device-dependent. And the method which is changing the operation of transfer printing increases the operation difficulty of transfer printing.

In this work, we explored a simple, low-cost, high-performance transfer printing method. Namely, AST method. The adhesive and liner of AST both can be dissolved in acetone so that there isn't interface contention between stamp/ink and ink/receiver substrate during "printing" process, so it can maximize the transfer printing efficiency. And the acetone soluble tape is inelastic so that it can maintain the exact arrangement of inks to realize high fidelity. By this method, inks can be transferred on variety of substrates, even curvilinear surfaces. And Si TFTs on sapphire substrate were fabricated by AST.

2. Transfer printing method

SOI wafer was cleaned by acetone, alcohol and DI water. Si inks and PR anchors were formed by lithography and etching process. Figures 1a-f show the main process of AST. Figure 1a shows that Si inks which were complete undercut etched. Then using AST picked up Si inks, as illustrated in Fig 1b. GaN/Sapphire substrate was selected as receiver substrate. Coupling the tape which acquired Si inks with receiver substrate, as shown in Fig 1c. The coupling system was fully immersed in acetone, as shown in Fig 1d. AST was dissolved in acetone. Then the receiver substrate was cleaned by DI water, as shown in Fig 1e. There are lots of tape residuals on receiver substrate and Si inks. Finally, receiver substrate was treated with O_2 plasma so that the tape residuals were fully removed, as shown in Fig 1f.

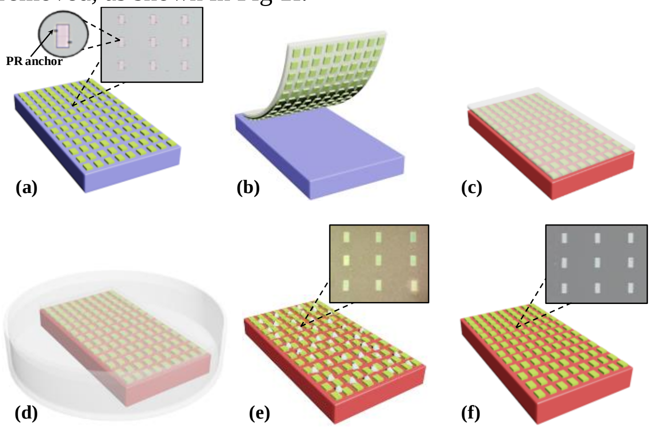

Fig. 1. Schematic illustration of AST process. (a) Si inks undercut etched on bottom substrate. (b) Si inks picked up by AST. (c) Coupling Si inks with receiver substrate. (d) Immersing the coupling system in acetone. (e) Receiver substrate after transfer printing. (f) Receiver substrate after O_2 plasma process.

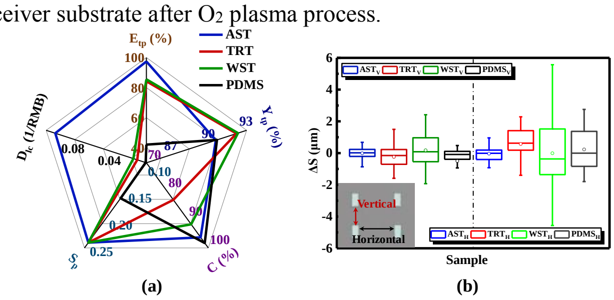

Fig. 2. Contrastive plots of the critical parameters of four transfer printing methods. (a) Efficiency (E_{tp}), yield (Y_{tp}), cleanliness (C), process simplicity (S_p) and low-cost degree (D_{lc}). (b) Location shift (ΔS).

3. Results and Discussion

Figure 2a shows the critical properties of four methods. Transfer printing efficiency (E_{tp}) was extracted basing on the equation $E_{tp} = (n_1/n_0)100\%$. "n_1" is the number of Si inks which are transferred onto receiver substrate. "n_0" represents the number of Si inks on donor substrate. AST has the highest E_{tp} up to 97.37% due to the printing process which doesn't involve interface contention. E_{tp} of TRT and WST is 84.21% and 85.53%, respectively. E_{tp} of PDMS is the lowest, which just is 42.11%. Transfer printing yield (Y_{tp}) was extracted basing on the equation $Y_{tp} = (n_2/n_1)100\%$. "n_2" is the number of Si inks which are intactly transferred onto receiver substrate without cracks or wrinkles. Y_{tp} of AST and PDMS are 90.54% and 90.63%. TRT and WST have higher Y_{tp}, 92.19% and 92.31%. Cleanliness (C) is derived from the equation $C = (n_3/n_2)100\%$. "n_3" is the number of Si inks which are clean without tape residuals in "n_2". Cleanliness (C) of PDMS is the highest up to 98.27%. PDMS is elastomeric and its fabrication process is extremely clean, so there are almost no residuals left on inks or receiver substrate. Cleanliness of AST is up to 96.27%. Although there was still most of adhesive (tape residuals) which isn't dissolved after being immersed in acetone left on inks and receiver substrate, it can be almost removed completely by O_2 plasma process. WST's cleanliness is up to 91.67%. TRT's cleanliness is the lowest, just 83.05%, due to certain residuals which can't be removed by O_2 plasma or Piranha solution. Process simplicity (S_p) is derived from the reciprocal of number of transfer printing process steps. The transfer printing processes of AST, TRT and WST all involve four steps, "picking up", "coupling", "releasing" and "removing residuals". However, Step Number of PDMS is six, including "cleaning mold", "preparation of PDMS", "curing PDMS", "cutting PDMS", "picking up" and "printing". In addition, "picking up" and "printing" are two difficult steps in PDMS due to the adhesion strength which is controlled by peeling velocity. Low-cost degree (D_{lc}) is derived from the reciprocal of unit price of the transfer printing stamps. TRT and WST have similar prices about 100 RMB. PDMS needs 1200 RMB. However, AST just costs about 10 RMB. Location shift (ΔS) is divided into two categories, vertical location shift (ΔS_V) and horizontal location shift (ΔS_H), as shown in the optical image of Fig. 2b. As shown in Fig. 2b, whichever method is used, there is still existing ΔS. The vast majority of ΔS_V and ΔS_H of all methods are within ±2 μm. ΔS_V and ΔS_H of AST are both minimum ($|\Delta S_V|$, $|\Delta S_H| < 0.5$ μm) and distributed uniform around zero. All the $|\Delta S_H|$ is larger than $|\Delta S_V|$ in each method, because stamps will suffer from slight tensile strain inducing the increase of $|\Delta S_H|$ when stamps pick inks up in horizontal direction. But positive and negative values of AST's ΔS_H are distributed uniform, due to a better stretching resistance of AST.

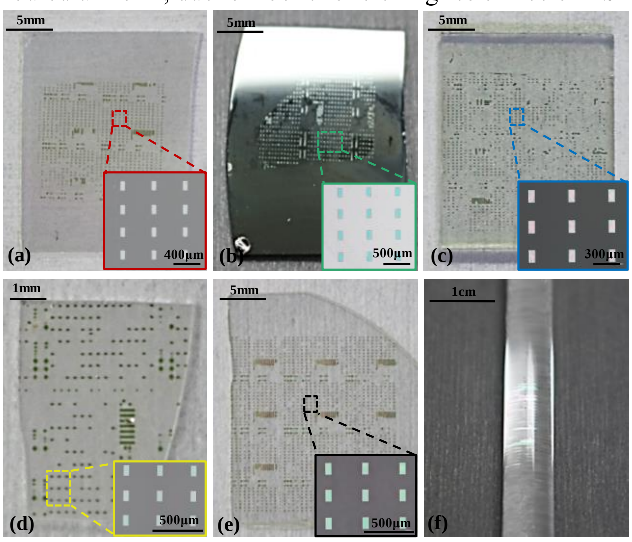

Fig. 3. Si inks transferred onto various alien substrates by AST. (a) AlGaN/GaN/Sapphire substrate. (b) Ge substrate. (c) FTO substrate. (d) Ga_2O_3 substrate. (e) Sapphire substrate. (f) Glass rod.

Figure 3a-f show that Si inks were transferred onto various alien substrates by AST. Figure 3a shows that Si inks were printed onto AlGaN/GaN/Sapphire substrate (E_{tp}=95.63%). Figure 3b shows Si inks were printed onto Ge substrate (E_{tp}=93.42%). AST doesn't work well on oxide substrates. As shown in Fig. 3c-d, Si inks were printed onto FTO and Ga_2O_3 substrates. And E_{tp} is 57.89% and 62.73%, respectively. But improvement can be realized by O_2 plasma process which can produce lots of suspension bonds on oxide substrates. These suspension bonds can make Si inks and oxide substrates bond more robustly. As shown in Fig. 3e, Si inks were transferred onto sapphire substrate (Al_2O_3) which was processed by O_2 plasma (E_{tp}=90.82%). Si inks also can be transferred onto receiver substrates which have curvilinear surfaces. As shown in Fig. 3f, Si inks were printed onto a glass rod.

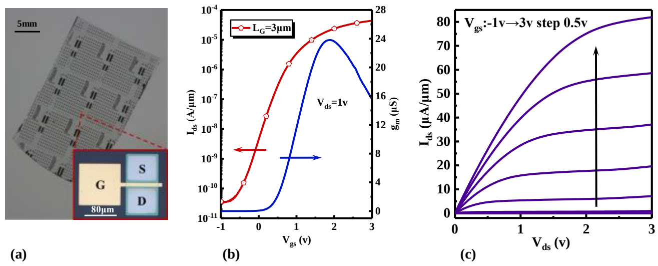

Fig. 4. Devices and its electrical characteristics. (a) Si TFTs on sapphire substrate by AST. (b) The transfer characteristics. (c) I-V characteristics.

Si TFTs on sapphire substrate were fabricated. Figure 4a shows Si TFTs on sapphire substrate. Figure 4b shows the transfer characteristics of TFTs. The gate length is 3 μm, and $I_{on/off}$ is up to 10^6. The peak transconductance is 24 μS and the threshold voltage is 1.03 V. Figure 5c presents I-V characteristics. The low resistance (0.81 Ω·mm) of the ohmic contacts was extracted in these devices.

4. Conclusions

Transfer printing process of AST doesn't involve interface contention between stamp/ink and ink/receiver substrate so that it maximize the transfer printing efficiency. It has satisfactory performances in E_{tp}, Y_{tp}, C, S_p, D_{lc} and ΔS. It can transfer Si inks onto various alien substrates, even curvilinear objects. Although it doesn't work well on oxide substrates, it can be improved by surface treatment on these substrates. Si TFTs can be fabricated on sapphire substrate by AST. All the results indicate that AST is an effective method in heterogeneous integration.

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References

[1] H. Lee *et al.*, *IEEE Electron Device Lett*. 33 (2012) 200–202.
[2] K. H. Lee *et al.*, *Appl. Phys. Express*. 9 (2016) 1–4.
[3] J. Ren *et al.*, *IEEE Electron Device Lett*. 38 (2017) 501–504.
[4] M. A. Meitl *et al.*, *Nat. Mater*. 5 (2006) 33–38.
[5] C. Linghu *et al.*, *npj Flex. Electron*. 2 (2018) 26.
[6] S. Kim *et al.*, *Proc. Natl. Acad. Sci.* 107 (2010) 17095–17100.
[7] S. Cho *et al.*, *Langmuir*. 32 (2016) 7951–7957.
[8] A. Carlson *et al.*, *Appl. Phys. Lett.* 98 (2011) 5–7.