Very Low Noise RF nMOSFETs on Plastic by Substrate Thinning and Wafer Transfer

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***Abstract*—A very low minimum noise figure ($NF_{\min}$) of 1.2 dB and a high associated gain of 12.8 dB at 10 GHz were measured for six-finger, 0.18-μm radio frequency (RF) metal-oxide semiconductor field-effect transistors mounted on insulating plastic following substrate-thinning ($\sim$ 30 μm) and wafer transfer. Before this process, the devices had a slightly better RF performance of 1.1-dB $NF_{\min}$ and a 13.7-dB associated gain. The small RF performance degradation of the active transistors transferred to plastic shows the potential of integrating electronics onto plastic.**

***Index Terms*—Associated gain, metal-oxide semiconductor field-effect transistor (MOSFET), minimum noise figure, plastic, radio frequency (RF).**

I. Introduction

A DIFFICULT challenge for Si-based radio frequency (RF) integrated circuits (ICs) is the poor Q-factor of the passive devices [1]–[10] arising from the low resistivity (10 Ω-cm) very large scale integration (VLSI)-standard Si substrates. This also degrades the RF gain and noise performance of the whole integrated circuit (IC). The performance of the RF passive devices can be improved by integration on high-resistivity Si substrates [1], using a micro-electromechanical system (MEMS) approach [2]–[4] or the ion-implant-translated semi-insulating Si technology [5]–[10]. However, the improved RF performance is traded off by the increased cost of added mask and process steps or package costs. Because plastic substrates are highly insulating, high-performance RF passive devices can be fabricated on them. For integration, the challenge is to avoid reducing the performance of the active devices on the plastic. This is vital for circuits integrated onto plastic [11], [12]. In this letter, we describe the performance of 0.18-μm RF metal-oxide semiconductor field-effect transistors (MOSFETs) mounted on plastic. After thinning down the Si substrate to 30 μm and bonding onto a plastic substrate the devices showed a low minimum noise figure ($NF_{\min}$) of 1.2 dB and a high associated gain of 12.8 dB at 10 GHz.

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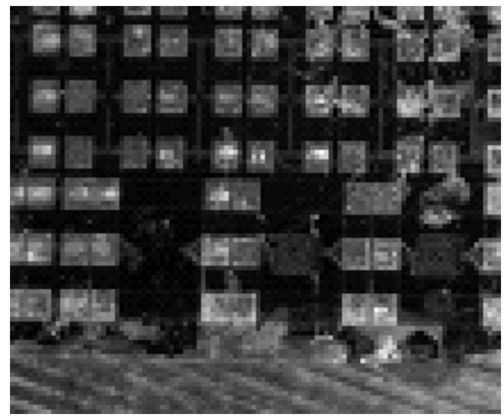


Fig. 1. Fabricated die on a transparent plastic substrate, with the surface of a wooden table as background.

This excellent RF performance is comparable with that of the original devices on the VLSI-standard Si substrates, which showed only 0.1-dB lower $NF_{\min}$ and a 0.9-dB higher associated gain. Such low noise and high gain RF MOSFETs at 10 GHz are important for future RF ICs on plastic, where it is economically advantageous to integrate large antennae pick-up coils on the cheap plastic substrates.

II. Experimental Procedure

In this study, we used 180-μm-thick polyethylene substrates, which had a resistivity of 10^8–10^9 Ω-cm. We designed the 0.18-μm MOSFETs with multiple fingers (six, 16, and 32 gate fingers) and a novel microstip line layout [13], which were then fabricated on 8-in wafers at an IC foundry [13]–[16]. The reduction of the gate resistance with increasing number of parallel fingers comes at the cost of increased dc power consumption. To achieve integration onto plastic, we first used inductively coupled plasma (ICP) dry etching followed by wet chemical etching to thin down the substrate of the die from 300 μm to 30 μm, although the full wafer thinning is also possible. For the dc, RF and noise testing the thinned-down devices were mounted onto the plastic using glue. A fabricated die with different nMOSFETs is shown in Fig. 1. It is transparent, showing the surface of a wooden table as background. The transparency is useful for integration with displays. The RF performances were measured using standard coplanar Cascade

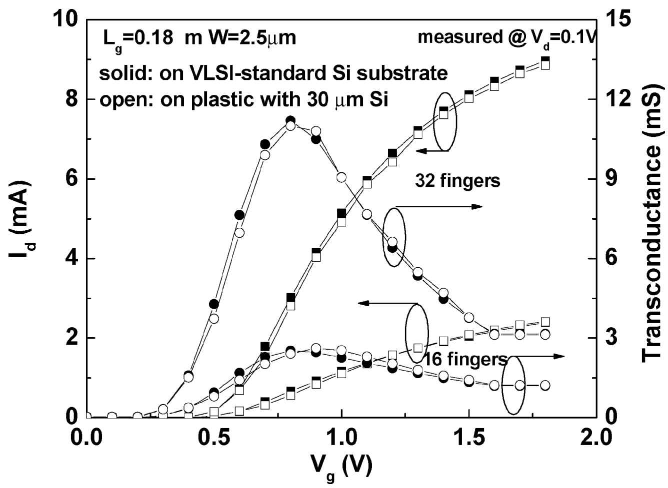
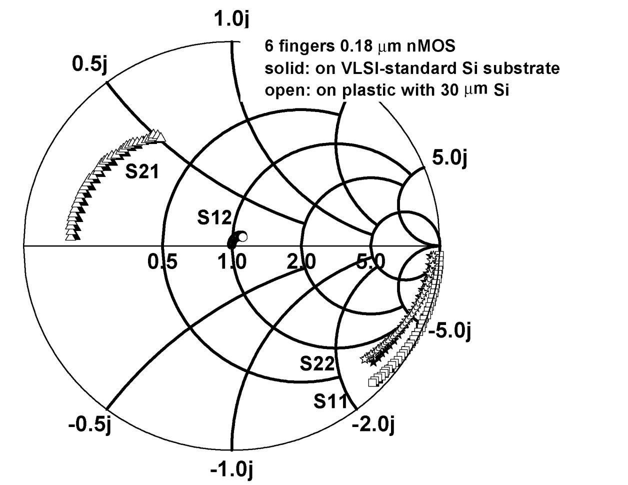
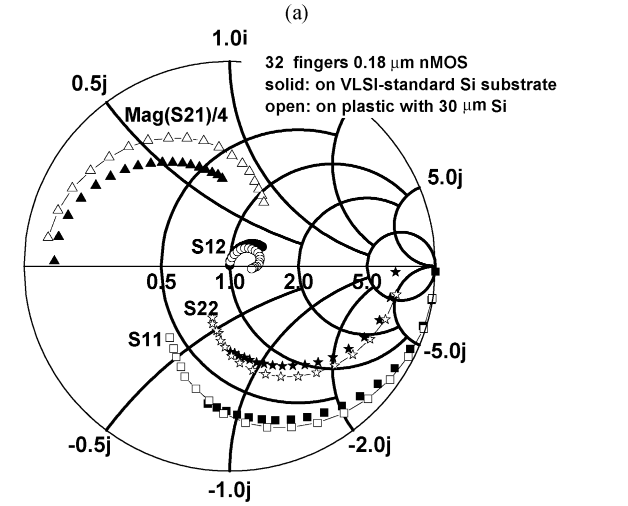


Fig. 2. Measured dc characteristics I_d–V_g and g_m–V_g curves for six and 32 gate-finger 0.18-μm RF MOSFETs on a VLSI-standard Si substrate and on plastic.



(a)



(b)

Fig. 3. S-parameters of six-finger and 32-finger 0.18-μm RF MOSFETs on a VLSI-standard Si substrate and on plastic. The devices were dc biased at $V_g = 1.2$ V and $V_d = 1.8$ V.

probes, an HP8510C network analyzer, and an ATN-NP5B noise parameter measurement system [13]–[16].

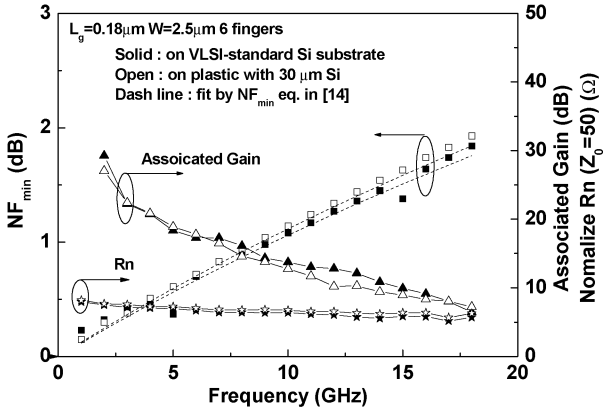
III. Results and Discussion

The dc characteristics of six- and 32-gate-finger 0.18-μm RF MOSFETs on a VLSI-standard Si substrate, and on plastic (following Si substrate thinning) are shown in Fig. 2. The I_d–V_g and g_m–V_g characteristics for both small and large gate-finger transistors on plastic are comparable with those on VLSI-standard substrates, suggesting that the Si substrate thinning and bonding on plastic did not cause any significant damage to the 0.18-μm RF MOSFETs.

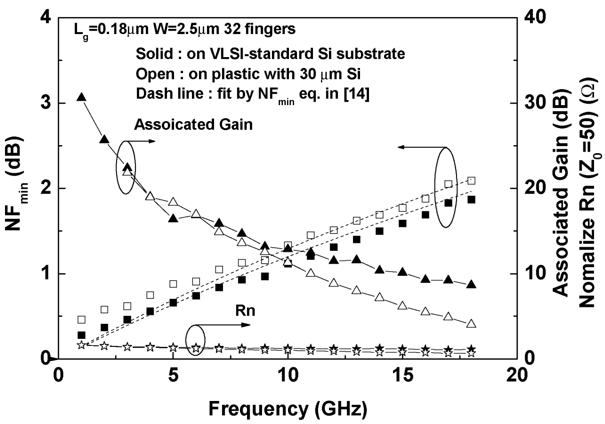
Fig. 3(a) and (b) compare the measured S-parameters of six- and 32-gate-finger 0.18-μm RF MOSFETs on the VLSI-standard substrate and on plastic. In contrast with the negligible changes in the dc characteristics, we found small degradations of S_{21}, the reverse coupling S_{12} and the input S_{11} and output S_{22}. These degradations increase with increasing number of gate fingers. Note that the degradation is not due to the thermal resistance, which is confirmed by the comparable dc I_d–V_g and g_m–V_g characteristics shown in Fig. 2. The 32-gate-finger device consumes only 22-mA current during S-parameter measurements, and therefore the thermal resistance effect is less significant at such a small dc power level. The degradation may be due to the larger area and greater damage during the ICP plasma thinning process. Similar degradation by plasma charging effect was also observed previously [18]. The data suggest that the RF characteristics are more sensitive than the dc characteristics to the substrate properties and their control is vital to achieve fully integrated RF ICs on plastic. Thinning Si substrates to < 20 μm causes severe degradation of the device characteristics. However, the advantage of ICP etching is the good thickness control and reproducibility. Thus, low damage etching is the key factor for the transfer technologies.

It is important to note that although transferring a thin semiconductor layer onto another substrate has been done by Si-on-insulator (SOI), Ge-on-insulator (GOI) [19], III–V compound epitaxial liftoff (ELO) [20], [21] methods etc., this work is the first report of transferring very thin (30 μm) Si RF devices onto plastic. The merits of RF Si-on-plastic are the excellent mechanical strength, good flexibility, acceptable RF performance ($f_t =$ 47 GHz and $NF_{\min} = 1.1$ dB at 10 GHz), and low cost that are not achievable by other technologies.

Fig. 4(a) and (b) show the measured $NF_{\min}$, *Rn* and associated gain for six- and 32-gate-finger 0.18-μm MOSFETs, respectively, on VLSI-standard Si substrates and on plastic with 30-μm Si. At 10 GHz, the six- and 32-finger RF MOSFETs on plastic show an $NF_{\min}$ of 1.2 and 1.3 dB, respectively, which is slightly higher than the 1.1 dB and 1.12 dB of those on standard substrates. The associated gain of 12.9 dB and 11.3 dB at 10 GHz for the six- and 32-finger RF MOSFETs on plastic, respectively, are also slightly degraded from the standard devices, which have gains of 13.8 dB and 12.8 dB. The noise resistance is also slightly degraded and is consistent with $NF_{\min}$ and associated gain. Although $NF_{\min}$ is degraded by 0.1–0.2 dB and the associated gain by 1–2 dB, the results are comparable with the best published values [13]–[17]. Thus the 0.18-μm transistors on plastic should be suitable for ultra-wide-band (3.1–10.6 GHz) applications.



(a)



(b)

Fig. 4. Measured $NF_{\min}$ and associated gain of six-finger and 32-finger 0.18-μm RF MOSFETs on a VLSI-standard Si substrate and on plastic.

IV. Conclusion

We have successfully transferred 0.18-μm MOSFETs (30-μm Si-body) onto plastic substrates. These devices showed excellent low noise performance (1.2 dB at 10 GHz), high associated gain (12.8 dB) and a small dc power consumption of 9 mA at 1.8 V. Such high performance RF transistors are vital to achieve ICs on plastic for wireless communication applications.

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