Low Noise and High Gain RF MOSFETs on Plastic Substrates

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***Abstract* — A low minimum noise figure (*NF_{min}*) of 1.2 dB and high associated gain of 12.8 dB at 10 GHz, were measured for 0.18 µm RF MOSFETs on plastic, made by substrate thinning (~30 µm), transfer and bonding. The performance can be further improved to 0.96 dB *NF_{min}* and 14.1 dB associated gain at 10 GHz, under applied tensile strain, using flexible Si on plastic. A 3.5 nH inductor on plastic showed a 55% higher Q-factor with a wider frequency range, compared with that on a Si substrate.**

***Index Terms* — RF Noise, associated gain, MOSFET, plastic.**

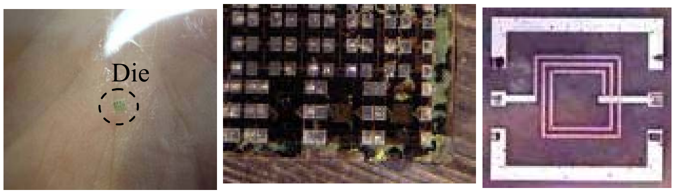
I. INTRODUCTION

The integration of RF ICs on plastic substrates is a useful technology for RF ID [1]-[2] and wireless display applications. Plastic substrates are not very lossy and are highly insulating (resistivity ~10^8-10^9 Ω–cm) - this is ideal for RF IC integration. In contrast, VLSI-standard Si substrates have a much lower resistivity of 10 Ω-cm; this results in large RF substrate loss and poor Q-factors [3]-[12]. The performance of RF passive devices on Si can be improved by integration on high-resistivity Si substrates [9], using MEMS [10]-[12] or ion-implant translated semi-insulating (10^6 Ω-cm) Si technology [3]-[8]. This improvement is traded-off by the increased cost of added mask and process steps, or package costs. A challenge for integrating RF ICs on plastic is that high performance transistors are required and need to be transferred from their Si substrates, and mounted on plastic with little performance degradation. Integration with high performance RF passive devices on the plastic substrate demands that the Si substrate of the RF transistors be thinned. In this paper we report a Si substrate thinning method and successfully transfer devices onto plastic. The 30 µm thick Si RF MOSFETs on plastic showed low minimum noise figure (NF_{min}) of 1.2 dB and high associated gain, 12.8 dB, at 10 GHz. This excellent RF performance on plastic is comparable with that on standard Si substrates [13]-[14]. Further improvement to 0.96 dB NF_{min} and 14.1 dB associated gain at 10 GHz is obtained under applied tensile strain [15], using flexible Si (30 µm thick) on plastic. The advantage of integrating RF devices on plastic is also evident from a 3.5nH inductor: the Q-factor is improved by 55% over a wide frequency range for a device on plastic, compared with one on Si. The devices with excellent low noise and high gain, combined with high-Q inductors are suitable for low-noise ultra-wide band (UWB) (3.1-10.6 GHz) applications.

II. EXPERIMENTAL PROCEDURE

Low-cost, highly-insulating polyethylene substrates were used in this study, having a resistivity of 10^8-10^9 Ω-cm. The multiple-gate-finger (6, 16, and 32) 0.18 µm MOSFETs were designed to reduce the gate-resistance-generated thermal noise [13]-[14], which is traded-off by the increase in DC power consumption. The Si substrate of the fabricated MOSFETs was thinned down from 300 µm (6 mil) to 30 µm, using Inductive-Coupled Plasma (ICP) dry etching followed by wet chemical etching. The ICP etching provides accurate thickness-control down to 30 µm and below. The thinned devices were glued onto the plastic for DC, RF and noise testing. Fig. 1(a) shows an image of the fabricated die on transparent plastic (holding by hand- the background), where an enlarged image is shown in Fig. 1(b). The transparent substrate reveals the surface of a wooden table as the background. To use the advantages of the plastic, we fabricated a 3.5 nH inductor on it using 2 µm thick Al. For comparison a 3.5 nH inductor was also fabricated in a VLSI-standard 1-Poly-6-Metal (1P6M) foundry process. In Fig. 1(c) shows an image of an inductor on plastic, where all process temperatures were kept below 100°C.

The device characteristics were measured using HP4155C for DC, HP8510C network analyzer for S-parameter and ATN-NP5B for noise measurements.



(a) (b) (c)

Fig. 1. (a) Image of a 30 µm thick RF MOSFET die on transparent plastic. (b) Enlarged image of a die of multiple-gate 0.18 µm MOSFETs on plastic. (Background is the surface of a wooden table.) (c) Image of an inductor fabricated on plastic.

III. RESULTS AND DISCUSSION

A. *Q-factor of a passive inductor fabricated on plastic*

Figure 2 shows the measured inductance and Q-factor for a ~3.5 nH inductor on plastic. For comparison, the data for a similar 3.5 nH inductor on VLSI-standard Si is also shown. The Q-factor of the inductor is improved by 55% from 6.4 (on Si) to 10 (on plastic). The resonance frequency is also improved from 9 GHz (on Si) to 12 GHz (on plastic). These improvements are similar to our reported ion-implant translated semi-insulating Si technology [4]. However, the area cost of plastic substrates is negligible compared with that of processed 8-in Si wafers using 0.18 µm technology. The low cost and high RF performance of passive devices are important advantages for plastic electronics, in addition to the optical transparency.

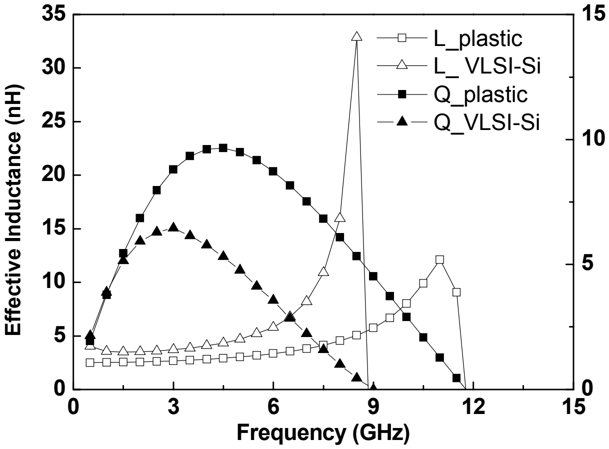


Fig. 2. The inductance and Q-factor of a ~3.5 nH inductor on plastic and VLSI-standard 1P6M Si. The maximum temperature for fabricating the inductor on plastic was 100°C.

B. *DC characteristics of nMOSFETs on plastic*

For the active transistors on plastic we first measured the DC I_d-V_d characteristics. Fig. 3 shows the I_d-V_d characteristic of 0.18 µm nMOSFETs with 6 gate fingers on plastic, where the Si substrate had been thinned down to 30 µm. For comparison, data for similar devices on a VLSI-standard Si substrate are also displayed. The almost identical I_d-V_d characteristics in Fig. 3, and I_d-V_g characteristics (not shown), suggest that the process of thinning down the Si substrate to 30 µm, then transferring and bonding it onto plastic, produced little degradation of the 6-finger 0.18 µm nMOSFETs. Similar observations were found for the DC I_d-V_d and I_d-V_g characteristics for 16- and 32-finger devices, suggesting that they are also suitable for further RF applications and examination.

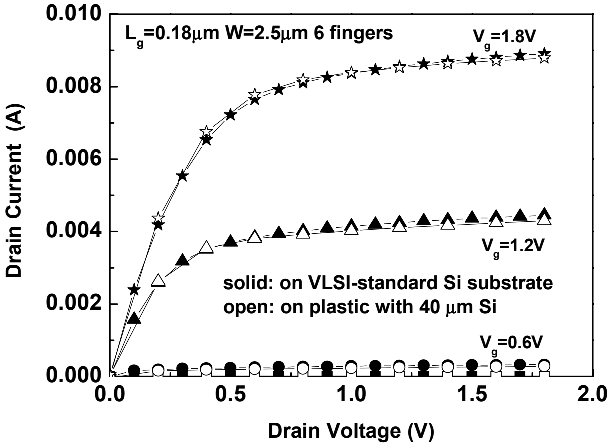


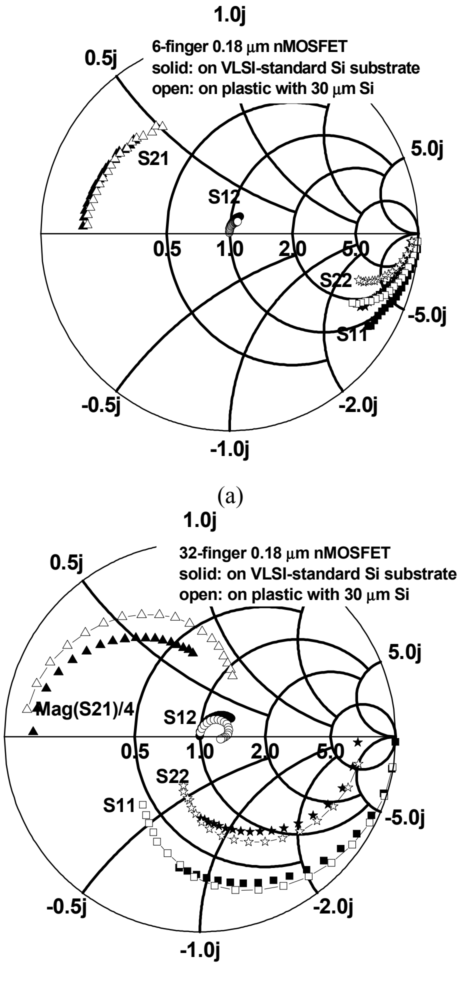
Fig. 3. Measured DC I_d-V_d characteristics for 6-gate-finger 0.18 µm RF MOSFETs on plastic, where the Si had been thinned down to 30 µm (open symbols). The I_d-V_d of similar devices on VLSI-standard substrates, before thinning down and bonding, is included for comparison (solid symbols).

C. *S-parameters and NF_{min} of nMOSFETs on plastic*

In Figure 4(a) we show the S-parameters of a 6-gate-finger 0.18 µm RF MOSFET on plastic, where the Si substrate had been thinned down to 30 µm. For comparison, the measured S-parameters of a device on a VLSI-standard substrate are also shown. There is little S_{21} gain degradation as well as little change in the reverse isolation S_{12}. The changes in both S_{11} and S_{22} are due to the increased substrate impedance when using plastic. The plastic helps reduce the substrate RF loss underneath the 6-finger MOSFETs. This result indicates that high performance RF MOSFETs can be realized on plastic.

Figure 4(b) shows a comparison of measured S-parameters for 32-gate-finger 0.18µm RF MOSFETs on a VLSI-standard substrate with those after thinning down the Si substrate to 30 µm, then transferring and mounting them onto plastic. Similar to the 6-gate-finger device case, both S_{11} and S_{22} are changed – due to the increased substrate impedance. However, the S_{21} gain reduces slightly - maybe due to the larger area of the device that has higher ICP plasma etching damage from the substrate-thinning step.

To examine the effect of the changes in S_{21} we compare the RF current gain of the 32-finger 0.18 µm MOSFETs before and after substrate thinning, transferal and mounting on plastic. Fig. 5 shows the RF current gain as a function of frequency. For the 32-finger 0.18 µm MOSFETs on VLSI-standard Si and plastic substrates, the $|H_{21}|^2$ follows the typical -20 dB/decade slope with increasing frequency. The 10 GHz gain of the 32-finger 0.18 µm MOSFET is only slightly decreased from 13.4 dB to 12.5 dB, before and after thinning down, respectively. This high RF gain suggests that the RF MOSFETs are suitable for integration onto plastic.



(a)

(b)

Fig. 4. Comparison of the measured S-parameters of (a) 6-finger and (b) 32-finger 0.18 μm RF MOSFETs, before (solid symbols) and after substrate thinning to 30 μm, transferal and mounting on plastic (open symbols).

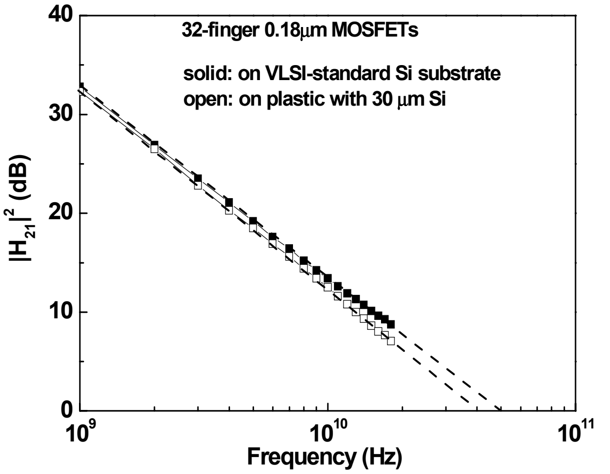


Fig. 5. Measured $|H_{21}|^2$ as a function of frequency for 0.18 μm MOSFETs before and after substrate thinning to 30 μm, then transferal and mounting on plastic.

RF noise in front-end MOSFETs is normally the dominant noise source for the whole of an RF system. Figure 6 shows the measured NF_{min} and associated gain of 6-gate-finger 0.18 μm MOSFETs on plastic substrates. For comparison NF_{min} of the reference devices on VLSI-standard Si substrates are also plotted. For the devices on plastic substrates, NF_{min} is 1.2 dB and a high associated gain of 12.8 dB was measured at 10 GHz. Only slightly better RF performance, 0.1 dB lower NF_{min} and 0.9 dB higher associated gain, were obtained for the control 0.18 μm MOSFETs at 10 GHz. These very small NF_{min} and associated gain differences, for the devices on plastic and on control Si substrates, are consistent with the nearly identical S-parameters shown in Fig. 4(a). In addition the DC power consumption is only 16 mW, at the excellent low noise and high associated gain conditions.

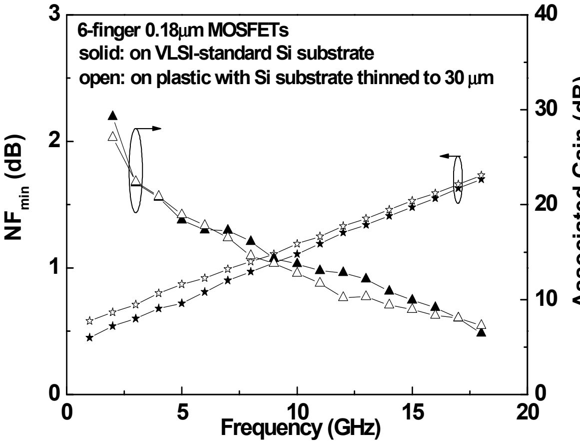


Fig. 6. Measured NF_{min} and associated gain of 6-finger 0.18 μm RF MOSFETs on plastic and on VLSI-standard Si substrates.

D. RF performance improvement using mechanically-applied tensile stress

An inherent merit of the 30 μm thin Si-body RF transistors on plastic is that the flexibility permits easy application of mechanical stress [15]. Fig. 7 shows the NF_{min} and associated gain of 6-finger 0.18 μm MOSFETs on plastic. Under ~0.4% tensile strain, a low NF_{min} of 0.96 dB and high associated gain of 14.1 dB are shown for the 0.18 μm devices on plastic at 10 GHz, which is consistent with the increased cut-off frequency (f_t) from 47 to 54 GHz. These values are an improvement from the unstrained case of 1.2 dB NF_{min} and 12.8 dB associated gain, and slightly better than the control devices on a VLSI-standard Si substrate.

The excellent results for RF MOSFETs on plastic, with or without tensile strain, are comparable with the best published data [13]-[14]. These very low NF_{min} (0.96-1.2 dB) and high associated gain (14.1-12.8 dB) 0.18 μm MOSFETs on plastic, are suitable for UWB applications.

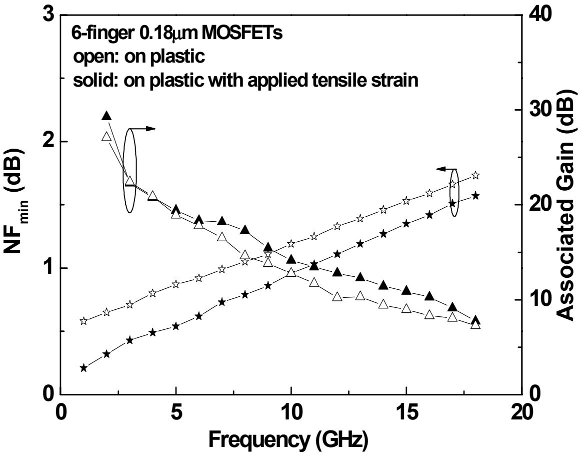


Fig. 7. Measured NF_{min} and associated gain of 6-finger 0.18 µm RF MOSFETs on plastic, with or without mechanically-applied tensile strain (~0.4%).

IV. CONCLUSIONS

We have demonstrated that 0.18 µm MOSFETs, mounted on plastic after substrate thinning and die transfer, show low noise of 1.2 dB and high associated gain of 12.8 dB, measured at 10 GHz. The high performance RF transistors, combined with high-Q passive inductors, are crucial components needed to create electronics on plastic for wireless communication applications.

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