Transmission Line Noise from Standard and Proton-Implanted Si

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Abstract **We have measured the NF_{min} of transmission lines on 10^6 ohm-cm proton implanted Si, Si-on-Quartz, and standard Si with top isolation oxide. Transmission lines on proton implanted Si shows the lowest NF_{min} of less than 0.2dB because of the low substrate loss due to the high resistivity. The proton implantation did not contribute to excess shot noise induced by carriers trapping and de-trapping because of the very small diffusion length to metal line.**

I. INTRODUCTION

In Si MOSFET based RF technology, one of the most important technology barriers is the substrate loss. This is because the increased power gain G_{max} for active transistors is typically less than 2dB [1] as device scaling down for one generation, but the substrate loss may be larger than 1dB at high frequencies. Further, high noise from substrate may be larger than noise generated by MOSFETs, which has a typical minimum noise figure (NF_{min}) of less than 1dB for advanced 0.18μm technology. Therefore, the Signal/Noise ratio from lossy Si substrates is becoming the limiting factor for RF circuits at higher frequency and may be even more important than active MOSFET. The lossy Si substrate is also one of the inferior points than semi-insulating GaAs or InP. Recently, we have published extremely high resistivity Si of 10^6 ohm-cm [2] that has 5 orders larger resistivity than the standard Si substrate and close to semi-insulating GaAs of typical 10^8 ohm-cm. The 10^6 ohm-cm high resistivity Si can be selectively formed on desired area by proton or Si ion implantation [3] but only proton can penetrate the entire Si wafer. The Mega-ohm-cm high resistivity is stable more than 400°C during VLSI back-end process and little front-end gate oxide integrity degradation is also observed [4] that makes process integration of this technology feasible. Although proton ion implantation has advantages of selectively forming insulating area on Si wafers, it is suspected that excessive noise may result from ion implantation induced traps [2]. This is an important concern because trapped carriers may be de-trapped and generate excessive high frequency noise [2]. In this paper, we have measured the transmission line noise on proton implanted Mega-ohm-cm resistivity Si and compared with standard Si and Si-on-Quartz (SiO_2) (SOQ). Extremely low noise of <0.2dB is measured on proton implanted Si but standard Si shows much higher noise of 0.5~1.1dB in the measured frequencies of 0.3-6GHz. The small noise in combining with low loss of <0.2dB that gives proton implanted Si a much higher S/N of 1.0-2.2 dB than standard Si. This amount of RF performance improvement in substrate loss is about one VLSI technology generation scaling down of MOSFETs.

II. EXPERIMENTAL PROCEDURE

Standard Si with typical ~10 ohm-cm resistivity and 1.5μm thermal oxide, SOQ with 2000Å 10 ohm-cm top Si, and proton implanted Si of 10^6 ohm-cm resistivity are used in this study. The 1.5μm thermal oxide on standard Si was grown at 1000°C to enssure good isolation quality. The substrate used before proton implantation is also the standard 10 ohm-cm Si and proton implantation can convert standard Si into 10^6 ohm-cm resistivity Si. Then 1000μm long transmission lines are formed on these wafers using 1μm thick Al line with 30μm width. Standard 2-port s-parameters are measured using HP8510B network analyzer up to 20GHz to characterize the power loss. RF noise figure and associate gain are measured using ATN-NP5B Noise Parameter Extraction System from 0.3 to 6 GHz that covers the most important frequency range for wireless communication.

III. RESULTS AND DISCUSSION

A. RF noise

Fig. 1 shows the measured RF NF_{min} for standard Si with 1.5μm top isolation oxide, SOQ, and proton implanted Si. The NF_{min} of standard Si shows a general increasing trend as increasing frequency, but proton implanted Si and SOQ show less frequency dependence. The reason why an increasing NF_{min} with frequency may be due to the substrate loss that can be modeled by a shunt $R_s+(R_p//C_p)$. The shunt pass can contribute to Re(Z) and becomes more lossy at higher frequencies even though the reactive components do not generate thermal noise. The above assumption can be understood by the smaller NF_{min} for transmission lines on SOQ than that on standard Si with isolation oxide, because of the smaller substrate loss in insulating Quartz (SiO_2). It is important to notice that the proton implantation process did not generate additional noise sources from implantation induced traps as evidenced from the even smaller noise than that of SOQ. The measured <0.2dB NF_{min} for transmission lines on proton implanted Si over the entire frequency range is close to the limitation of our measurement system.

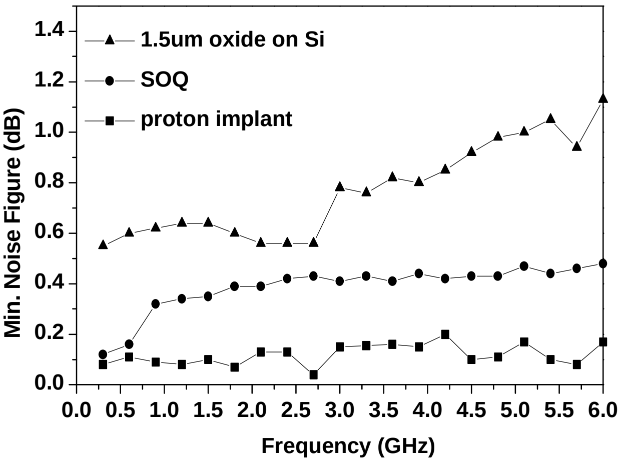

Fig. 1. The measured RF NF_{min} for standard Si with 1.5μm top isolation oxide, SOQ, and proton implanted Si. The NF_{min} of standard Si shows an increasing trend as increasing frequency.

We have also plotted the frequency dependent associated gain in Fig. 2. As shown in Fig. 2, the proton implanted Si shows the lowest loss among others and the standard Si with isolation oxide is the worst. The reason why SOQ has a poorer associated gain and higher noise than proton implanted Si is due to the top 2000Å Si of ~10 ohm-cm resistivity, even though Quartz may have higher resistivity than proton implanted Si. Because transmission line is a gainless device, the measured loss (0dB minus associated gain) is about equivalent to NF_{min}. Therefore, the associate gain shows almost the same trend as NF_{min}. The smaller associated gain in standard Si than SOQ is due to the higher loss in Si substrate, because of much thinner 2000Å Si on the insulating quartz substrate of SOQ.

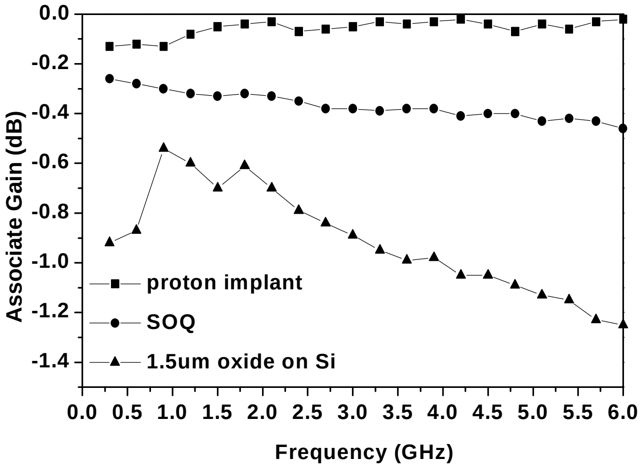

Fig. 2. The frequency dependent associated gain for standard Si with 1.5μm top isolation oxide, SOQ, and proton implanted Si. The standard Si with 1.5μm top isolation oxide is the worst.

To further investigate the RF performance dependent substrate effect, we have also plotted the S/N ratio and the result is shown in Fig. 3. The S/N ratio for proton implanted Si with values of -0.1~-0.2dB is the highest and the worst is standard 10 ohm-cm resistivity Si with S/N of –1.2~-2.4dB. This trend is the same as NF_{min} and associated gain. The S/N ratio improvement of 1.0~2.2 dB is near the same as one VLSI technology generation for improving MOSFET RF performance. The smaller S/N, higher loss and higher NF_{min} for standard Si are the limiting factors for Si based high frequency RF amplifiers that are used in the wireless LAN or the optical fiber communication.

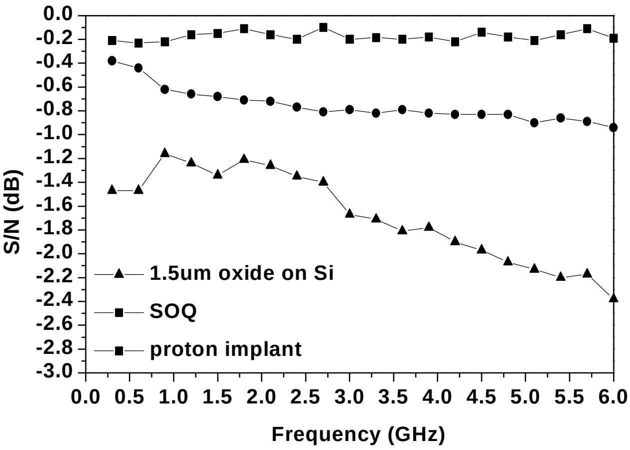

Fig. 3. S/N ratio of standard Si with 1.5μm top isolation oxide, SOQ, and proton implanted Si. The proton implanted Si shows the best performance.

B. Model

We have further used an equivalent circuit model shown in Fig. 4 to simulate the RF noise. The equivalent circuit for proton implanted Si gives an nearly open circuit to ground with very large shunt resistances and small shunt capacitances in both input and output ports. The model for proton implanted Si then becomes a simple transmission line between two ports. The small series resistance is due to the finite Al metal thickness and skin effect, and the small inductor is due to the transmission line itself. A similar equivalent circuit model can be also used for SOQ. However, the fitted equivalent circuit model shows smaller shunt impedance in both ports that gives a slightly larger NF_{min} and loss than proton implanted Si. Much lower shunt impedance is obtained from the same equivalent circuit model in standard 10 ohm-cm resistivity Si with isolation oxide that explains the poor NF_{min} and loss.

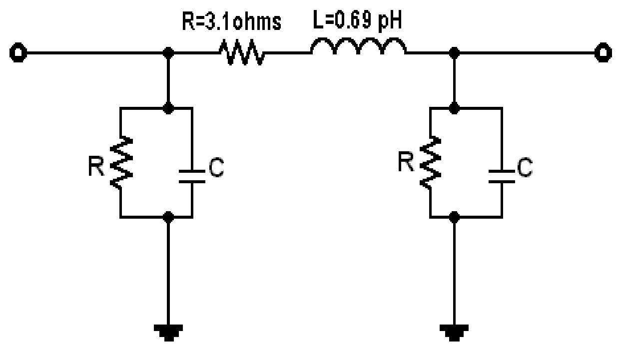

Fig. 4. The equivalent circuit model used for s-parameter and noise simulations. The substrate loss can be modeled by decreasing shunt resistance and increasing shunt capacitance.

We have further simulated the s-parameters using the equivalent circuit model in Fig. 4. As shown in Fig. 5, excellent matching between measured and modeled s-parameters up to 20 GHz is obtained that indicates the good accuracy of the simple model. Furthermore, good agreement of measured NF_{min}, noise resistance (R_n), and NF spectra with simulated results can also be obtained as shown in Fig. 6, by using this simple equivalent circuit model. The primary NF_{min} for proton implanted 10^6 ohm-cm resistivity Si is coming from thermal noise generated from the resistance of the transmission line. We have also investigated the RF noise for SOQ and standard Si with 1.5μm isolation oxide. From the equivalent circuit model, the higher noise is therefore generated from the shunt pass loss to the ground.

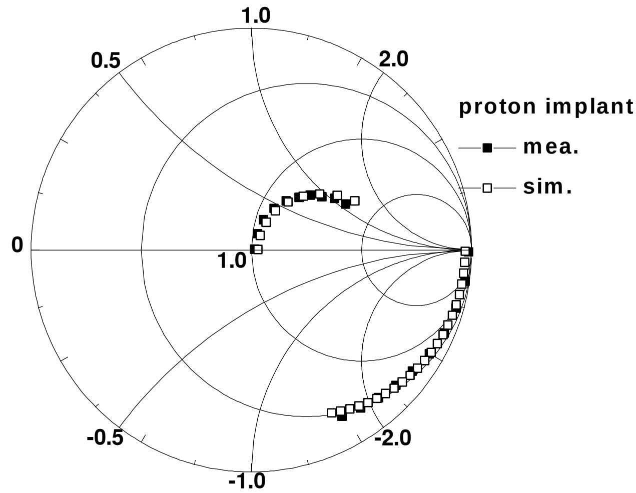

Fig. 5. Measured and simulated s-parameters for the transmission line on proton implanted Si up to 20 GHz. Excellent matching between measured and modeled data suggests the good accuracy of model in Fig. 4.

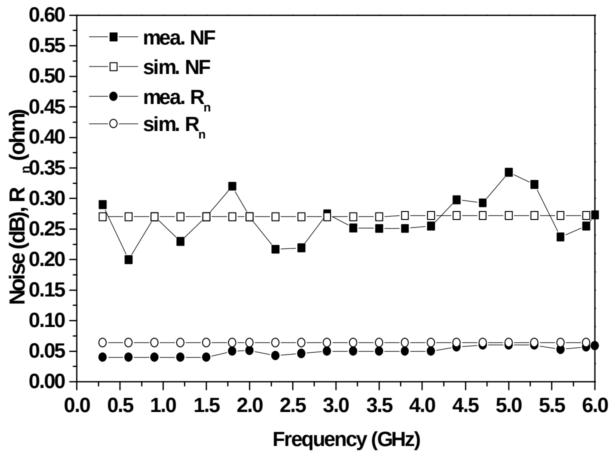

Fig. 6. Measured and simulated R_n and NF_{min} for proton implanted Si. Good agreement between measured and model data suggests the good accuracy of simple equivalent circuit model.

C. Microscopic mechanism

It is interesting to ask why there is no proton implantation induced excess noise for transmission lines. Fig. 7 shows the microscopic carriers trapping and de-trapping model and the traps are generated by proton implantation. A deep trap of ~0.45eV is measured from the conduction band using temperature dependent conductance, which is close to mid bandgap of Si.

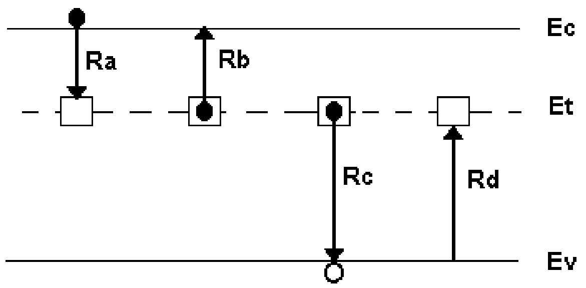

Fig. 7. The proton implantation generated trap model. Carrier trapping and de-trapping may give the excessive shot noise.

The carriers trapping and de-trapping generate shot noise if carriers are collected by transmission lines. However, the efficiency of collecting the generated shot noise over the Al-Si depletion region should be low, because of the small carrier lifetime (τ) of ~1ps [2] and the small carrier diffusion length:

$$l = \sqrt{D^2} = \sqrt{(\frac{kT}{q} «)^2} \quad (1)$$

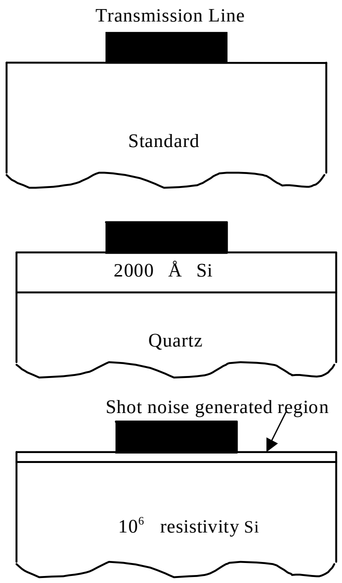

Fig. 8. Different substrate structures for standard Si (top), SOQ (middle), and proton implanted Si (bottom). The thinner top noisy Si for SOQ and proton implanted Si gives lower noise than standard Si.

Because of the small mobility in proton implanted amorphous Si close to 1 cm^2/Vs, the estimate diffusion length is only 16Å. Therefore, the RF noise is mainly coming from thermal noise generated by resistance rather than trap generated shot noise. The reason why measured NF_{min} decreases from standard Si, SOQ, and proton implanted high resistivity Si can be understood as increasing substrate resistance and decreasing top noisy Si thickness as shown in Fig. 8.

IV. CONCLUSION

The NF_{min} is the worst in standard Si with isolation oxide and the best in proton implanted Si. The proton implantation process does not generate excess noise because of the small carrier mean diffusion path due to the implantation formed amorphous structure. The excellent NF_{min}, low loss, and good process integration capability can shrink the RF performance gap between Si and GaAs.

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