Low RF loss and noise of transmission lines on Si substrates using an improved ion implantation process

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Abstract -- **Very low power loss ≤ 0.6 dB at 110 GHz and noise of < 0.25 dB at 18 GHz have been measured on transmission lines fabricated on Si substrates and implanted with proton. In contrast, much worse power loss of 5 dB and higher noise of 2.5 dB were measured without implantation. This large improvement arises from the high resistivity by proton implantation, which was also done after forming the transmission lines and at a reduced energy of ~ 4 MeV for easier process integration into current VLSI technology.**

I. INTRODUCTION

Owing to the rapid evolution of MOSFET technology, Si has been used for RF applications, because of the inherent excellent integration capability. However, the high substrate loss and cross-talk, due to the low resistivity of Si (~10 Ω-cm), have become some of the main technology challenges to realize high performance Si MMICs. Even advanced SOI technology shows little improvement in substrate loss and cross-talk because very thick isolation is necessary to block the microwave penetration for RF performance improvement. Recently, we have developed a simple ion implantation process [1]-[6] which can significantly increase the Si resistivity from the standard 10 Ω-cm to ~ 10^6 Ω-cm [1]. This high resistivity can be maintained at 400 °C and has little side-effect on masked gate-oxide integrity, even after being integrated into a VLSI back-end process. Excellent antennas and transmission lines up to 20 GHz have been demonstrated [5]. In this paper we show data on the RF noise, at up to 18 GHz, and the RF loss, up to 110 GHz, of transmission lines fabricated on ion-implanted Si. Excellent RF noise of < 0.25 dB to 18 GHz and very low power loss, ≤ 0.6 dB up to 110 GHz, have been measured on proton-implanted transmission lines on Si. This is much better than for transmission lines on oxide-isolated Si without the implantation. The modified implantation sequence, done after device fabrication, not only reduces the disruption to a VLSI process line but also extends the maximum possible operation frequency from 590 GHz to 1100 GHz. Reducing the implantation energy to ~ 4 MeV also makes the approach feasible for production, through the use of a simple thick photoresist.

II. EXPERIMENTAL PROCEDURE

Standard 4-in Si wafers, with a resistivity of 10 Ω-cm, were used in this study. An additional 1.5 μm thermal SiO_2 was grown to increase the substrate isolation. Ion implantation of protons, from an ion cyclotron, was done to reduce the substrate loss further. The ion implantation was performed either before, or after device fabrication. In the former case the wafer would face a subsequent 400 °C thermal cycle in the backend process. For manufacturing considerations, we have reduced the implantation energy from 15 MeV to ~ 4 MeV by using an additional energy absorber. To study the RF noise dependence on the substrates, coplanar transmission lines of 1000 μm length, 30 μm width, and 4 μm thickness were fabricated using Al metal. Two-port S-parameters were measured up to 110 GHz using an HP 8510C network analyzer and de-embedded from dummy pads. The RF noise figure and associated gain were measured from 1 to 18 GHz using an

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ATN-NP5B Noise Parameter Extraction System. To study the maximum possible operation frequency, beyond the upper limit of the network analyzer, we used a femto-second laser to measure the response time [3].

III. RESULTS AND DISCUSSION

A. RF noise

Fig. 1 shows the measured RF noise of transmission lines fabricated on 1.5-μm SiO_2 isolated Si substrates, with or without the different proton implantation processes. The standard Si gives a noise figure of 0.5 ~ 2.5 dB/mm from 1 GHz to 18 GHz. This amount of RF noise is even larger than the noise from MOSFETs [7]-[8], and scaling down the VLSI technology from 0.18 to 0.13 μm MOSFET has negligible noise improvement [7]. Thus, the *RF noise from transmission line will contribute significant* noise to MMICs. In contrast, the 10^{16} cm^{-2} proton implanted Si has a much improved RF noise of ≤ 0.25 dB in the 1 ~ 18 GHz range. The excellent RF noise is consistent with the high associated gain as shown in Fig. 2. The negative associated gain is due to the transmission lines being passive devices. The proton-implanted Si, done at reduced ~ 4 MeV energy after the backend process, shows excellent low noise and high gain – comparable with the high-energy 15 MeV implant done before the backend process. This suggests that it could be used for process integration into current VLSI technology.

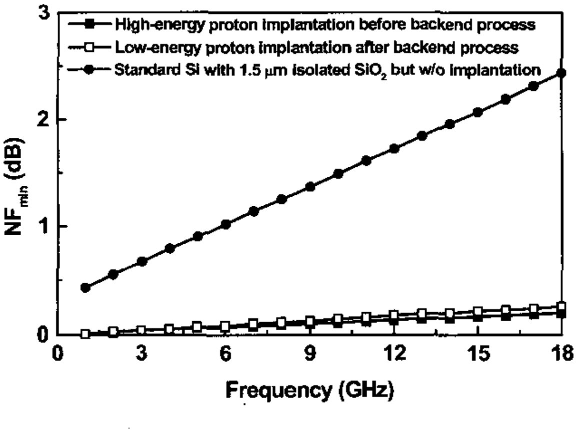

Fig. 1. The measured RF NF_{min} for standard Si with 1.5-μm top isolation oxide, applied with or without the different proton implantation processes. The NF_{min} of the standard Si increases rapidly with increasing frequency.

To investigate the dependence of the RF performance on the substrates, we compare the S/N ratio in Fig. 3. For proton-implanted Si the S/N ratios of -0.1~ -0.8 dB/mm are the highest, and the sequence of implantation has little effect. The worst S/N ratio is shown by the standard Si with an S/N of -0.9~ -5 dB/mm. This trend is the same as NF_{min} and the associated gain. The S/N ratio improvement of 0.8 ~ 4.2 dB is frequency dependent indicating good potential for proton-implanted Si in RF applications, especially in the frequency range up to 18 GHz.

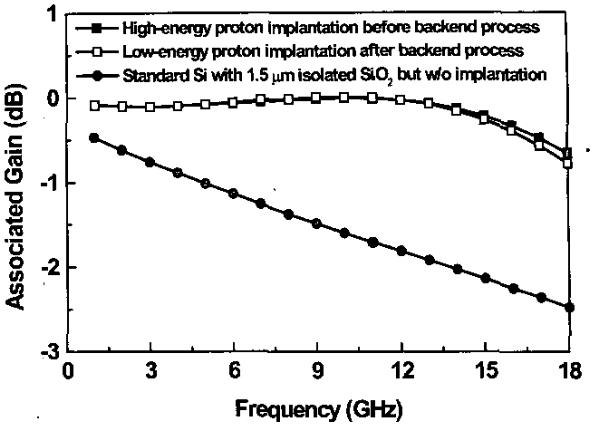

Fig. 2. The frequency dependent associated gain for standard Si with 1.5-μm top isolation oxide, applied with or without the different proton implantation processes. The standard 1.5-μm SiO_2/Si without implantation shows very poor associated gain.

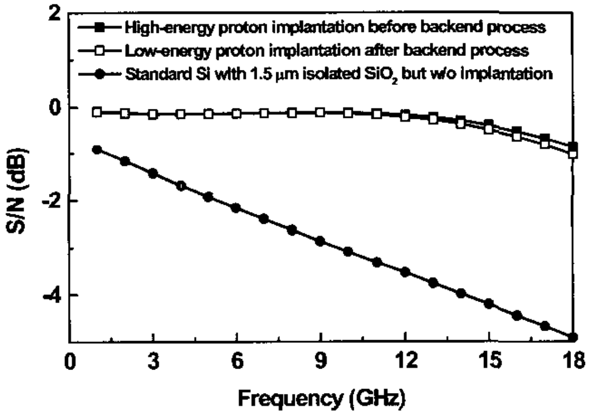

Fig. 3. S/N ratio of transmission lines fabricated on 1.5-μm SiO_2/Si substrates with or without the different proton implantation process. The S/N improves largely for transmission line with proton implantation, and the implantation sequence has little effect.

B. RF loss

We have also measured the S-parameters of the 1000-μm long transmission lines up to 110 GHz, as shown in Fig. 4. The lines are symmetrical so only S_{11} and S_{21} are shown. Both S_{11} show inductive behavior at the lower frequencies, starting at the center and spiraling clockwise.

The additional loops may be due to resonances. The magnitude of transmission gain S_{21} on both the proton-implanted Si stays relatively high over the whole frequency range, while the standard Si shows a smaller $|S_{21}|$. This result is consistent with the poor associated gain and S/N shown in Figs. 2 and 3.

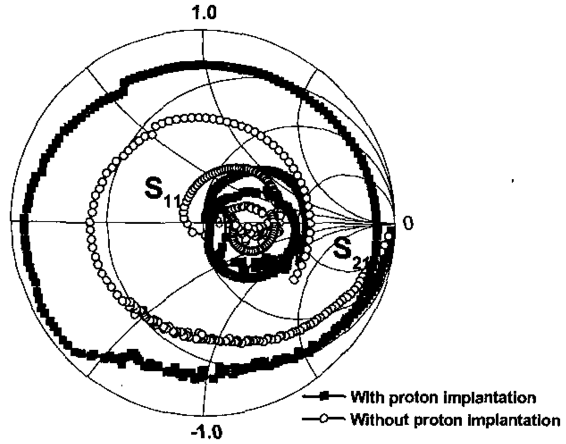

Fig. 4. The measured S_{11} and S_{21} of 1000-μm long transmission lines on the standard 1.5-μm SiO_2/Si substrates applied with or without implantation. The magnitude of S_{21} on the transmission line implanted with proton is larger over the whole frequency range than the same transmission line without implantation.

The power loss of the transmission lines, up to 110 GHz, is shown in Fig. 5. For those on 1.5 μm SiO_2-isolated standard Si, the loss increases monotonically with increasing frequency - this is consistent with the RF associated gain shown in Fig. 2. The ~ 5 dB higher power loss, poorer RF noise, and much lower associated gain are some of the severe drawbacks of conventional Si RF technology. In contrast, the 10^{16} cm^{-2} proton-implanted Si provides improved power loss of ≤ 0.6 dB/mm up to 110 GHz and is close to the ideal case.

To probe the maximum operation frequency beyond the upper limit of the network analyzer, we used a femto-second laser method [3]. As shown in the Fig. 6, response times of 0.9 ps (1100 GHz) and 1.7 ps (590 GHz) were measured for implantation after and before device fabrication, respectively. These values are due to the high defect-density-related fast trap rate that gives high resistivity [3]. At high enough frequency, the trapped carriers can follow the signal and become active. The activated carriers at high frequencies will make the semi-insulating Si become conductive. The reduced maximum operation frequency, when the implantation was done before device fabrication, is due to the backend thermal cycle, which anneals out some of the defects.

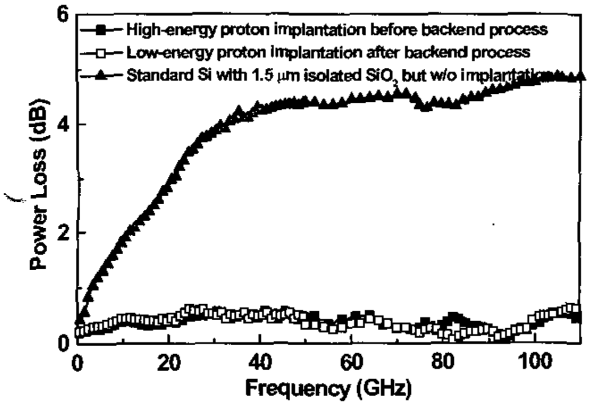

Fig. 5. Measured power loss of transmission lines on the standard 1.5-μm SiO_2/Si substrates up to 110 GHz, with and without the different proton implantation processes. The loss for the transmission line implanted with proton is much lower.

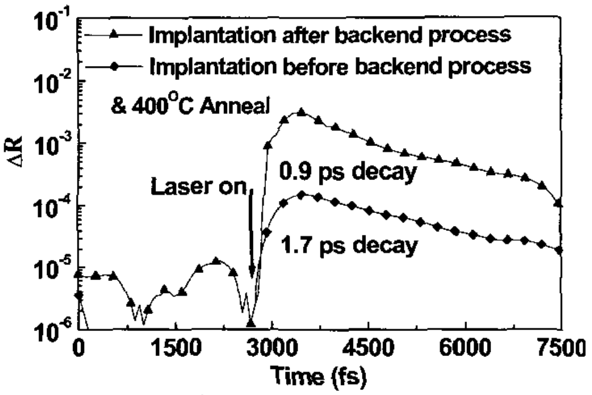

Fig. 6. Measured carrier response by femto-second laser method. Response times for implantation after and before device fabrication is 0.9 ps (1100 GHz) and 1.7 ps (590 GHz), respectively.

C. Simulated Results

In addition we have simulated the S-parameters to study the dependence of the RF loss on different substrates. Fig. 7 shows the measured and simulated S-parameters, up to 18 GHz, for the transmission lines fabricated on variously treated Si substrates. The equivalent circuit schematic for the transmission line on Si with or without proton implantation appears in the insert. The S-parameters of the proton-implanted transmission lines on Si, applied before and after the backend process, are almost identical. The good agreement between the measured and modeled S-parameters suggests that the equivalent circuit model is appropriate. The extracted R_s for the standard Si case is ~350 Ω, much smaller than the 22500 Ω for the proton-implanted devices.

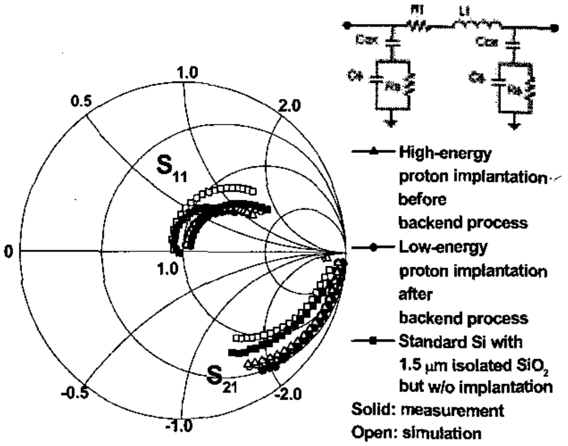

Fig. 7. Simulated and measured S-parameters of transmission lines on Si substrates up to 18 GHz, applied with or without the different proton implantation processes. The inserted figure is the equivalent circuit model. Good agreement indicates that the model is appropriate.

Using the same model, we also calculated the RF noise, shown in Fig. 8. Good agreement between the measured and modeled noise is shown, assuming that the noise source is the thermal noise of the shunt R_s. The relatively small substrate resistance for the standard Si increases the thermal noise of the transmission lines. The reason why the implantation process does not contribute to the excess noise in the 1 to 18 GHz range is due to the fast trapping time (high frequency) as shown in Fig. 6.

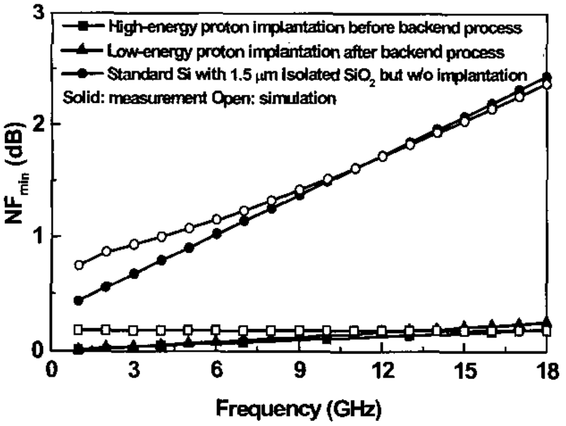

Fig. 8. Simulated and measured minimum noise figure of transmission lines on Si substrates, applied with or without the different proton implantation processes. The noise source may result from the substrate shunt resistance R_s, since a good fit is obtained.

IV. CONCLUSIONS

We have achieved extremely low RF noise and power loss for transmission lines on proton-implanted Si that suggests potentially good process integration capability with VLSI technology. The good isolation by proton implantation is directly related to the figure-of-merit of the RF performance for the Si transmission lines.

ACKNOWLEDGEMENT

We would like to thank D. C. Nio at National Chung-Shan Science Research Inst. for help with the RF measurements. This work has been supported by NSC (90-2215-E-009-044).

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