Integrated Antennas on Si With Over 100 GHz Performance, Fabricated Using an Optimized Proton Implantation Process

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***Abstract*—We have improved the performance of integrated antennas on Si for possible application in wireless communications and wireless interconnects. For practical VLSI integration, we have reduced the antenna size and optimized the proton implantation to a low energy of ~ 4 MeV with a depth of ~ 175 μm. To avoid any possible contamination, the ion implantation is applied after device fabrication. Excellent performance such as very low RF power loss up to 50 GHz, record high 103 GHz antenna resonance, and sharp 5 GHz bandwidth have been achieved.**

***Index Terms*—Antenna, implantation, loss, RF, transmission line.**

I. Introduction

THE increased interest in integrated antennas on Si is due to pervasive emerging wireless communication applications, and the possibility of their use as high-frequency wireless circuit interconnects [1]–[3]. However, major technological challenges for Si RF devices are the large RF loss and parasitic capacitances [4]–[8], due to the high conductivity of Si substrates. To overcome this problem we have developed an ion-implanted Si process to increase the standard Si wafer resistivity of 10 Ω-cm to 10^6 Ω-cm [2], [8]–[11]. This results in improved RF loss in transmission lines and integrated antennas on Si up to a frequency of 20 GHz. Although the resulting high resistivity is stable after backend processes [9], there are potential contamination issues resulting from the use of an implantation energy of several MeV and the high dose of $> 10^{15}$ cm^{-2}. Such high implantation energies are unavailable in commercial ion implanters, thus a cyclotron ion source with minimum energy of ~ 15 MeV was previously used. Also commercial photoresists are not appropriate for patterning at such high energies.

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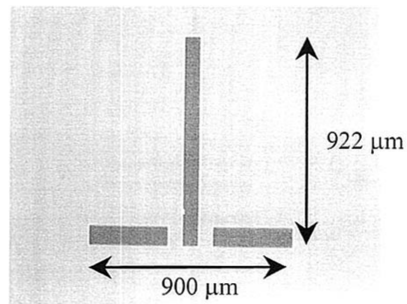

Fig. 1. Schematic of a fabricated monopole antenna.

The high-energy reaction can emit harmful radiation which can degrade the gate oxide integrity

$$^{28}_{14}\mathrm{Si} + ^{1}_{1}\mathrm{H}(> 8\ \mathrm{MeV}) \longrightarrow ^{25}_{13}\mathrm{Al} + ^{4}_{2}\mathrm{He}; \quad ^{25}_{13}\mathrm{Al} \xrightarrow{\beta^{+} decay} ^{25}_{12}\mathrm{Mg}. \tag{1}$$

In this paper, we describe an optimized ion implantation process and improved upper operation frequency of 103 GHz. The implantation energy has been reduced to ~ 4 MeV without sacrificing the RF performance, and can be masked using a simple thick resist. To avoid contamination the implantation has been applied after device fabrication. The resulting excellent RF performance and simple process can reduce the RF performance gap between Si and GaAs.

II. Experimental Details

Standard 4-in, p-type Si wafers with ~ 10 Ω-cm resistivity were used in this study and an additional 1.5 μm oxide was grown on Si substrate to increase the RF isolation. Next, integrated monopole antennas were designed for operation at 40 GHz, fabricated on oxide-isolated Si using 4 μm thick Al, and patterned as shown in Fig. 1. The antenna was fed by a coplanar waveguide (CPW) with size smaller than that in our previous work [2] due to the higher frequency. The antenna area was then implanted with 15 MeV protons at a dose of 10^{16} cm^{-2}. To optimize the proton implantation energy, we have simulated the power loss [12] of 1000 μm long transmission lines with different proton-implantation depths. As shown in Fig. 2(a), the simulated power loss decreases monotonically with increasing proton-implantation depth and

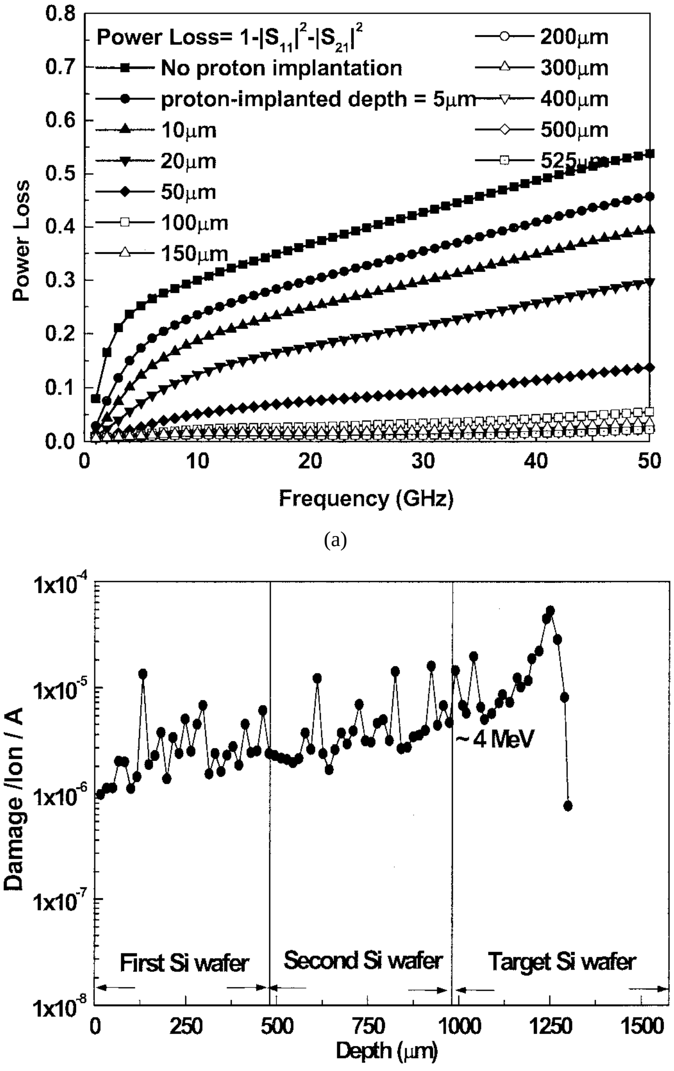

Fig. 2. (a) Simulated power loss of 1000 μm transmission lines with different proton-implanted depths and (b) the simulated proton implantation damage profile for an implant energy of ~ 15 MeV, which is reduced to ~ 4 MeV after first two Si wafers.

gradually saturates when the depth exceeds 150 μm. Thus we have placed two extra Si wafers above the target device wafer to reduce the implantation energy from 15 MeV to ~ 4 MeV with an effective depth of $\sim$ 175 μm, as shown in Fig. 2(b). The antenna characteristics before and after proton-implantation were measured using an HP 8510C network analyzer.

III. Results and Discussion

Fig. 3 shows the measured power loss of 1 mm long transmission lines. The power loss for conventional oxide-isolated Si is very high and $\sim 65\%$ of the incident power is lost at 50 GHz. The proton implantation greatly reduces the RF power loss even by using the low energy proton implant of ~ 4 MeV MeV with implanted depth of $\sim$ 175 μm. Very low power loss, $< 6\%$ of incident power up to 50 GHz, was obtained using the lower implantation energy of ~ 4 MeV applied after device fabrication.

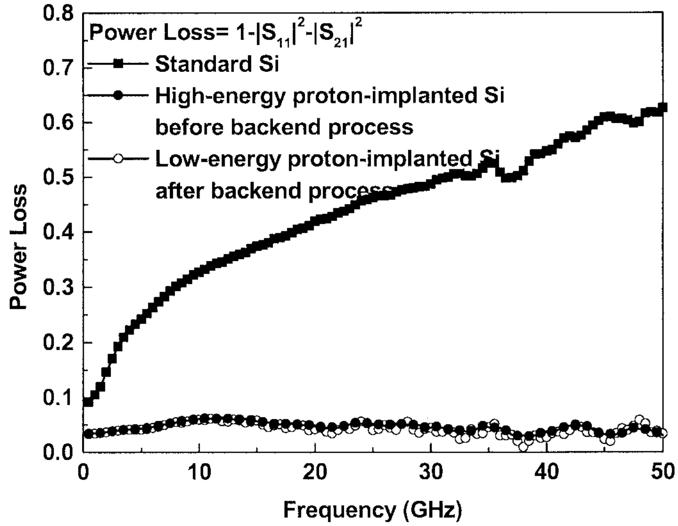

Fig. 3. Measured power loss of 1000 μm coplanar transmission lines. Very low loss, up to 50 GHz, was measured on the proton-implanted Si.

This is almost the same as that obtained using the higher implantation energy of 15 MeV, which was performed before device fabrication. This measured result is consistent and close to the simulated data shown in Fig. 2(a). The negligible dependence of the RF loss on implant sequence is important, to avoid contamination issues for process integration. The use of the lower energy implantation can also avoid degrading the gate oxide with radiation generated by nuclear reactions. Moreover, the smaller implantation depth can be easily masked by commercial thick photoresists, to enable the selective creation of semi-insulating regions below the desired devices.

We have also measured the antenna characteristics. Fig. 4(a) shows the antenna resonance behavior of the monopole antennas. Poor antenna resonance with large loss over a wide frequency range is observed for antennas fabricated on the standard Si which had a 1.5 μm isolation oxide. The large bandwidth is due to the effects of both the large RF loss, shown in Fig. 3, and the antenna resonance but it is unsuitable for practical applications. In sharp contrast, the ~ 4 MeV proton implantation, performed after device fabrication, can greatly improve the substrate loss, and the sharp resonance at 48 GHz. A second harmonic resonance at 103 GHz was measured for the monopole antenna fabricated on 1.5 μm oxide-isolated Si, which was subsequently implanted with protons. To the best of our knowledge, this is the highest reported operation frequency for an integrated antenna on Si. The small -20 dB bandwidth of 5 GHz at the 103 GHz resonance also indicates excellent antenna characteristics, which can be used for wireless communication, as well as chip-to-chip wireless interconnects. Fig. 4(b) also shows the horizontal polarized antenna radiation patterns, at a resonant frequency of ~ 40 GHz. The small-sized antennas were measured on finite-sized planes, diced from Si wafers. The RF probe does affect the E-plane pattern results, which accounts for the asymmetry and the low power levels at certain angles. The large ripples in the patterns indicate surface-wave diffraction due to substrate modes, arising in the thick Si substrate (525 μm, $\sim\lambda_d/4$). Note that the antenna gain with the proton implantation is significantly larger than

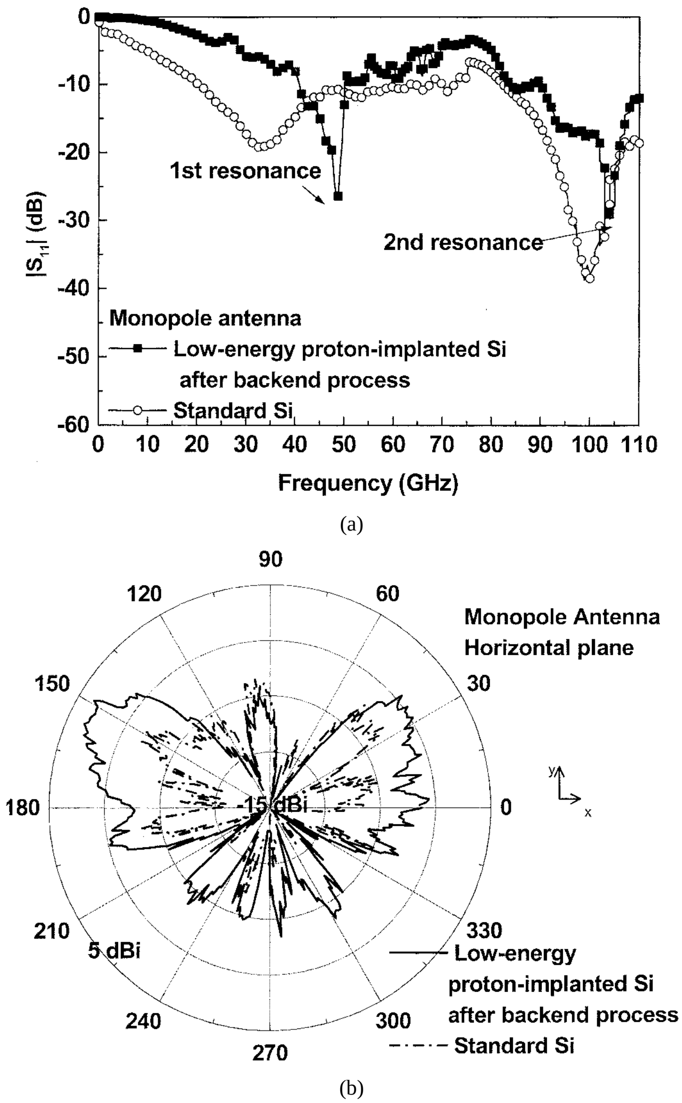

Fig. 4. Measured (a) S_{11} and (b) horizontal polarized radiation pattern of the monopole antennas. The second resonance frequency at 103 GHz is the highest reported for integrated antennas on Si.

that without, for both average and peak values of 4.2 and 6.4 dBi—this is consistent with the power loss of the transmission lines in Fig. 3.

IV. Conclusions

We have demonstrated high performance integrated antennas on Si, fabricated using an optimized proton implantation method for process integration. Sharp antenna resonance at 103 GHz was measured, indicating the great potential to integrate this process into current VLSI technology for wireless communication and wireless interconnects.

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