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（博士課程）
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論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	電子電気　系 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of (Philosophy)
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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

This thesis titled "Dual-Layer Proton Irradiation on CMOS On-Chip Passive Devices for Sub-THz Circuit Performance Enhancement," consists of six chapters.

Chapter 1, "Introduction," discusses the future 6G wireless communication technology requirements and the importance of utilizing the sub-terahertz band to fulfill these requirements. The passive component shrinkage in the sub-terahertz band enables on-chip passive implementation, reducing interconnect loss and improving system integration. However, low substrate resistivity on CMOS chips significantly degrades the performance of the on-chip passive components. Ion irradiation is the most promising method to increase substrate resistivity. It can be applied to all passive components as a post-process over the existing chip fabrication process, reducing its implementation cost. However, the conventional ion irradiation method suffers from high fluence requirements to achieve thermal stability, leading to low irradiation throughput and large unusable silicon area. Therefore, this thesis aims to formulate a more efficient and cost-effective ion irradiation profile to enhance the performance of CMOS on-chip sub-terahertz passives.

Chapter 2, "Analysis of Conventional Ion Irradiation," provides an overview of the conventional ion irradiation mechanism and its process parameters. This chapter explains the underlying theories connecting the irradiation parameters, such as ion fluences, species, and energy, with the characteristics of the resulting high-resistivity region, such as its depth, resistivity, thermal stability, and margin distance requirement. Proton was chosen as the ion species because it has the lowest mass, enabling the usage of a low-energy cyclotron to penetrate the typical 300 μm thick substrate of a CMOS chip. Analysis of proton defect generation across substrate depth indicates that high-energy, passing through protons at shallow depth generates fewer defects than low-energy protons near their target depth. In contrast, the parasitic surface conduction phenomenon significantly reduces resistivity at the Si-SiO_2 interface located at shallow depth, increasing defects required to increase resistivity and achieve thermal stability. This mismatch results in high fluence requirements in conventional single-layer proton irradiation to compensate for low defect generation efficiency at the Si-SiO_2 interface.

Chapter 3, "Dual-Layer Proton Irradiation," proposes a new irradiation profile where, in addition to the main irradiation, additional irradiation is targeted at the Si-SiO_2 interface to mitigate the parasitic surface conduction effect efficiently by utilizing the high defect generation efficiency around the irradiation target depth. This separation leads to overall fluence reduction on both the main and interface irradiation, reducing the total fluence compared to conventional irradiation. The dual-layer irradiation parameters are optimized experimentally, resulting in a thermally stable total fluence of 4×10^{14} cm^{-2}, or 60% reduction compared to the 10^{15} cm^{-2} required in the conventional case. This fluence reduction leads to a shorter irradiation time and decreases the margin distance requirement by 56% from 50 μm to 22 μm, reducing the unusable area on the chip. The impact of irradiation on metal structure was evaluated, with measurement results showing minimum to no impact on metal resistivity.

Chapter 4, "300GHz-Band CMOS On-Chip Vivaldi Antenna," demonstrates the effects of the proposed dual-layer proton irradiation on a sub-terahertz CMOS on-chip antenna. The Vivaldi architecture was chosen for its broadband and end-fire radiation characteristics, which are required for the 2D end-fire array implementation when the chip area becomes larger than the antenna area at the sub-terahertz band. For large-scale array applications, the antenna was optimized for beamwidth instead

of gain, resulting in a smaller antenna area of 500 μm × 500 μm. Comb-shaped slots were added outside of the antenna flanges to suppress energy back-flow due to the short taper length. The antenna was fabricated in a 65 nm CMOS process, with the substrate thinned to 50 μm to mitigate higher-order surface wave propagation. Measurement results show that dual-layer proton irradiation improves antenna gain from 2 dBi to 6 dBi, increases efficiency from 32% to 87%, and shows no degradation after annealing.

Chapter 5, "300GHz-Band CMOS On-Chip Chip-to-Waveguide Transition," demonstrates the effects of the proposed dual-layer proton irradiation on a sub-terahertz CMOS on-chip chip-to-waveguide transition. The transition uses a patch radiating element and utilizes the gold bump formed by the flip-chip process and the PCB top metal to form a back-short, enabling the transition to radiate through the back of the chip and allowing operation in flip-chip condition. The transition was fabricated in a 65 nm CMOS process in a back-to-back configuration for evaluation, with the substrate thinned to 50 μm to mitigate higher-order surface wave propagation. The measurement result shows that dual-layer proton irradiation reduces the transition insertion loss from 4.9 dB to 2.8 dB or around 2.1 dB improvement.

Chapter 6, "Conclusion and Future Work," summarizes the achievements of this paper and discusses future research prospects, emphasizing the need for improving process reliability, automating the optimization flow, and implementation on full-scale transceiver systems on the sub-terahertz band.