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# Propagation loss in crystalline silicon photonic waveguides due to gamma radiation

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***Abstract*—Silicon photonics has been demonstrated to have application in high data capacity scenarios. It would be desirable to use such technology in harsh environments where gamma radiation may be present, such as space or high energy physics experiments. In this article, the effect of such radiation is studied for passive silicon photonic waveguides. We demonstrate a correlation between optical power overlapping with the waveguide core/cladding interface and show that partially etched rib waveguides are less sensitive to performance degradation as a function of waveguide geometry. Additionally, we show that the post-exposure performance of these waveguides can be improved through heat treatment.**

***Keywords—Silicon photonics; gamma radiation effects; integrated optical communication***

## I. Introduction

Silicon photonics is an enabling CMOS compatible technology for optical interconnects, has demonstrated high bandwidth and low power consumption capabilities [1], and has found applications in roles such as data centers and optical interconnects [2]. The high capacity and energy efficiency offered by silicon photonics can also be utilized in high radiation environments such as space vehicles [3] and high-energy physics experiments [4]. It has been shown previously that radiation hardened (rad hard) CMOS is required for microelectronic activity in radiation environments, due to the degradation of materials and device performance, which can be attributed to ionizing radiation (gamma (γ) and X-ray radiation) and heavy ion radiation [5].

Here we explore the effect of total ionizing doses of γ-radiation on passive silicon photonic waveguides. Although typical silicon photonic systems will rely on more complex components than passive waveguides, the waveguide is the most fundamental building block on which many of these devices are based on (e.g. modulators, photodiodes). Additionally, silicon photonic waveguides are the media in which optical data is transmitted in, and it is therefore critical to understand how the performance of these waveguides is impacted in radiation environments before properly characterizing performance at the system level.

We find an increase in propagation loss in irradiated silicon photonic waveguides, which is attributed to an accumulation of charge at the silicon – oxide ($Si/SiO_2$) interface [6-8]. We experimentally verify this by showing that this change in loss has a positive correlation to the overlap of the power of the guided mode with side walls of the waveguides, and as a direct consequence show that fully etched strip waveguides are less sensitive to γ-radiation than the partially etched rib waveguides.

## II. Background

Our silicon photonic waveguides are dielectric waveguides with the core material of silicon (Si) and cladding material silicon dioxide ($SiO_2$). The modal distribution of the fundamental transverse electric (TE) mode of such waveguides is displayed in Fig. 1. These waveguides play roles in dense photonic integrated circuits (PIC's) due to the high index contrast, Δ, they provide ($\Delta \cong 2$). It has been shown that scattering due to sidewall roughness is a dominating source of loss in un-irradiated silicon photonic waveguides [9-11]. This loss can be reduced through reducing the sidewall roughness at the $Si/SiO_2$ interface [10], or through making the waveguides sufficiently wide to reduce modal power overlap with the sidewall interface. As the loss due to sidewall roughness decreases, the dominating source of loss is observed to come from the material loss in silicon, which arises from the background carrier concentration in the silicon film.

After being exposed to high energy γ-radiation (~ 1 MeV), holes can become trapped at the $Si/SiO_2$ interface [6-8]. Photons in the energy range of ~ 1 MeV are not energetic enough to cause lattice defects in either the silicon or oxide regions, so we can therefore associate variation in performance of the irradiated optical waveguides to the accumulation of this space charge region near the $Si/SiO_2$ interface, which can be seen as the black contours in Fig. 1.

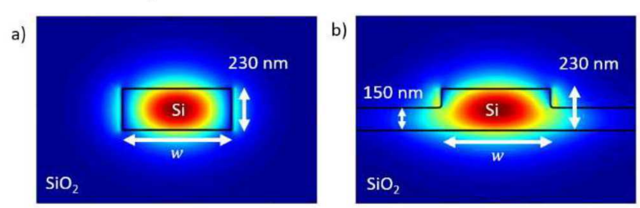


Fig. 1 – The transverse electric (TE) modal distribution in a) fully etched strip waveguides and b) partially etched rib waveguides of width $w = 1$ μm.

## III. Experiment and Results

In order to measure propagation loss for a waveguide of specific geometry, arrayed waveguide structures (AWS), analogous to a 1x1 arrayed waveguide grating (AWG), are fabricated using a passive silicon photonic process consisting of an 80 nm partial silicon etch, a 230 nm full thickness etch, and cladding in a 2.4μm high density plasma (HDP) oxide. The

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AWS consist of several waveguides of incrementally longer lengths, where the waveguide width and etch (full or partial) is held constant for each individual AWS. Loss is measured through employing a phase sensitive variation of the cut-back method, in which transmission through each of these arrayed waveguides is simultaneously measured [11]. Loss of the fundamental TE mode can then be extracted through comparing the relative transmission through each waveguide.

The AWS are irradiated using a cobalt 60 ($^{60}Co$) source with 130 rad/s dose rates. Room temperature of the AWS is maintained during irradiation by flowing room temperature (24 C°) air over the samples. Fully and partially etched AWS of varying widths are irradiated until a dose of 100 krad ($100 \times 10^3$ rad) or 1 Mrad ($10^6$ rad) has been absorbed.

At each of the $Si/SiO_2$ interfaces in the waveguide cross section depicted in Fig. 1, we expect an accumulation of trapped holes in the oxide region near the interface [6-8], and an accumulation of electrons in the silicon near the interface due to conservation of charge. Any modal overlap with this charge will lead to an increase in propagation loss. As the waveguide geometry changes, this distribution of the guided optical mode will change, and therefore the excess loss due to gamma radiation is expected as a function of waveguide geometry, particularly the etch type and width. Propagation loss is measured in several fully and partially etched AWS with different widths both before and after irradiation. The excess propagation loss is then calculated through subtracting the pre-exposure loss from the post-exposure loss. The resultant difference is then the excess loss due solely to the irradiation and is plotted in Fig. 2 as a function of waveguide width for both fully and partially etched waveguides.

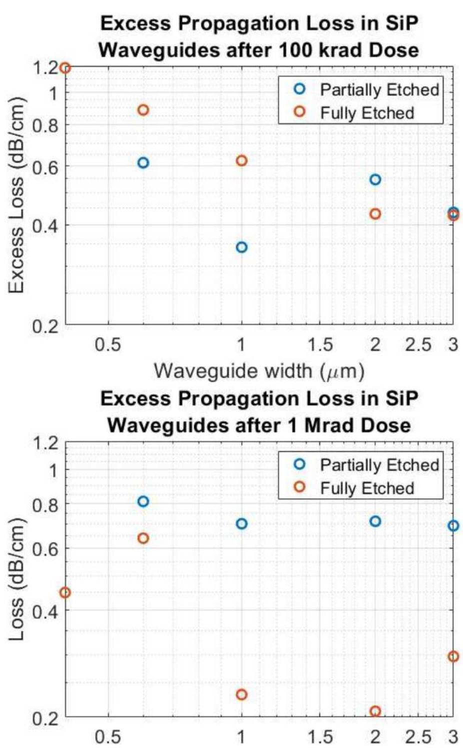


Fig. 2 – Measured excess loss in irradiated waveguides with a 100krad dose (top) and 1 Mrad dose (bottom) versus the associated waveguide width.

From Fig. 2, it is clear that the excess loss associated with fully etched waveguides depends more on waveguide width than that of partially etched waveguides. This is an expected result, because the modal overlap near the $Si/SiO_2$ varies with width more rapidly for fully etched waveguides than partially etched, due to a large majority of the mode being contained in the silicon slab region of the waveguide, where no $Si/SiO_2$ interface is present (as seen in Fig. 1). As a consequence, excess loss is reduced at wider waveguide widths, because the guided mode will become more confined in the waveguide core as the waveguide dimensions are increased, reducing the modal overlap near the $Si/SiO_2$ interface and radiation induced charge.

The excess loss does not vary much even when the absorbed dose is increased by an order of magnitude. To better understand this, an AWS with 3 µm wide partially etched waveguides is then irradiated incrementally, such that propagation loss can be measured after increasing doses have been absorbed into the sample. The results of this study are depicted in Fig. 3, where we see that the excess propagation loss minimally increases over an absorbed dose spanning two orders of magnitude. This indicates that the amount of accumulated charge in the oxide region does not change appreciably at higher radiation dosages, and that the overall radiation sensitivity of silicon photonic waveguides is low once a dose of roughly 10 krad has been absorbed.

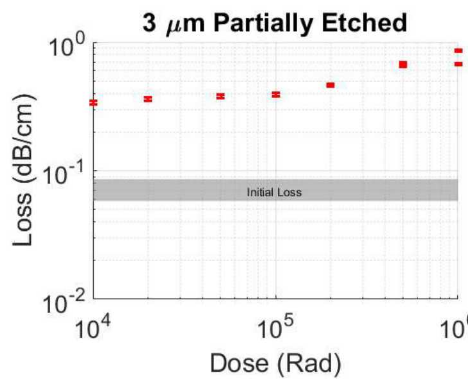


Fig. 3 – Measured propagation loss of a 3 µm partially etched waveguides at various absorbed dosages and its pre-exposure propagation loss.

Excess loss can be reduced post-exposure through a thermal anneal, in which the induced charge becomes neutralized [8]. If sufficient thermal energy is supplied to the traps at the $Si/SiO_2$ interface, the trapped carriers will gain enough energy to neutralize the associated charge, therefore decreasing the excess propagation loss due to irradiation. Each irradiated AWS is heated to 200° C for a duration of 2 hours before propagation loss is measured again, and the resultant change of loss is displayed in Fig. 4. As predicted, loss is improved in every AWS. The relative improvement in propagation loss can be most clearly seen in the case of the fully etched waveguides (regardless of absorbed dose), which as stated earlier, is attributed to the overlap of the mode and $Si/SiO_2$ interface varying more dramatically with waveguide geometry than the partially etched waveguides.

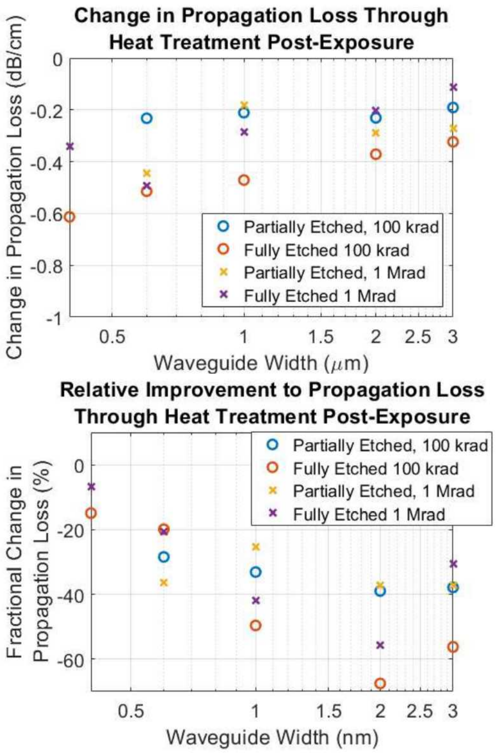


Fig. 4 – Measured change in propagation loss after heat treatment is applied to the each of the irradiated AWS (top) and relative improvement to propagation loss after heat treatment (bottom).

## IV. Conclusion

We have demonstrated an increase in propagation loss in silicon photonic waveguides after exposure to γ-radiation. This excess loss is associated with the creation of charge near the $Si/SiO_2$ interface of the waveguide upon exposure of radiation. Partially etched waveguides, as a function of waveguide width, experience less variation in excess loss, which is be expected because the modal overlap of the fundamental mode does not vary strongly with waveguide width for partially etched waveguides, and most of the mode is contained in the slab of the waveguide, where there does not exist any $Si/SiO_2$ interfaces. This suggests that for partially etched waveguides, wide range of widths can be implemented in harsh environments, whereas the fully etched waveguides would more sensitive to excess loss due to radiation with respect to waveguide geometry.

Additionally, we have shown that once an appreciable radiation dose has been absorbed into our silicon photonic waveguides, the change in excess propagation loss is small. These results indicate that these waveguides can be implemented scenarios where large amounts of radiation are expected for short periods of time, or where smaller amounts of radiation are present for long periods of time, showing the versatility of using systems based around silicon photonic waveguides in harsh environments.

Lastly, the versatility of our silicon photonic waveguides is further demonstrated by showing that although excess propagation loss occurs during irradiation, waveguide loss can be improved through heat treatment by allowing the source of the excess loss, the charge accumulation at the $Si/SiO_2$ interface, to neutralize through recombination. This shows that silicon photonic systems can potentially be reused for several experiments in which radiation is present, implying the practicality for silicon photonic systems for application in harsh environments.

## Acknowledgment

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