Method for high phase accuracy trimming of MZIs via Ge ion implantation and electrical annealing

April M. Logan [a], Xia Chen [a], Xingshi Yu [a], Weihong Shen [a], Xingzhao Yan [a], Weiwei Zhang [a], Goran Z. Mashanovich [a], Graham T. Reed [a], David J. Thomson [a]
[a] Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK
e-mail: aml4g19@soton.ac.uk

Phase tuning is essential for many silicon photonic devices to correct phase errors that have occurred due to fabrication variations. Currently microheaters are commonly used to thermally tune devices however this requires a constant power to be supplied to the components, which makes it unattractive for large-scale circuits with many hundreds or thousands of components. Ge ion implantation and annealing is a method that can be used to create trimmable components in which the refractive index of the implanted waveguides can be permanently changed after fabrication, without requiring a constant power to maintain the tuning (it is non-volatile). This method is therefore also suitable for the creation of large-scale programmable circuits.

Ge ion implantation causes lattice damage to the crystalline structure of the silicon waveguide and at a certain implantation dose, it will become amorphous (as it is 100% damaged) which results in an increase of the refractive index to 3.96 [1]. Annealing the implanted silicon above 400°C, will cause the silicon to begin to recrystallize and its refractive index will start to decrease. Fully annealing at temperatures between 600°C to 700°C [2] allows the refractive index to be recovered (3.48). Therefore by partially annealing, it is possible to tune the refractive index across a range of values. Annealing can be done electrically (via microheaters fabricated on chip) or with a specialized laser setup. Trimming with microheaters can be carried out at the wafer scale [3] or after packaging each die and can be carried out in parallel, decreasing the time it takes to trim or program large circuits.

Localized sections of Ge ion implanted waveguides can be introduced in various components to make them phase trimmable or programmable, for example, ring resonators [3, 4] and directional couplers [5] but in this work MZIs (Mach-Zehnder Interferometers) were used (Figure 1). High trimming accuracy is important to ensure the desired phase can be closely reached. This work puts forward a method of electrical annealing using voltage pulses that provides a higher trimming accuracy than previously demonstrated (0.025π was demonstrated in [6] via laser annealing and <0.01π was demonstrated in [3] via electrical annealing).

The method to electrically anneal the MZIs involved sending a series of voltage pulses to the microheater. Between successive pulses a voltage step was applied which was dependent on the average phase change brought about by the previous three voltage pulses as summarized in Table 1. Figures 2a and 2b show the accumulative phase change and the phase change between successive voltage pulses using this process respectively. Figure 2a also shows the voltage being applied across the microheater during the entire annealing process. Annealing began at a power of approximately 35mW and the device was fully annealed at a power of approximately 110mW.

Conclusion:
This work presents a method for annealing Ge ion implanted waveguides which can be used for phase trimming or creating programmable photonic components with high resolution of phase tuning. Using the developed electrical annealing process a minimum phase accuracy of 0.0054π was demonstrated, with potential for a much higher phase accuracy in the future.

[1] Yu et al, Journal of Lightwave Technology. 39, 15 (2022)
[2] Yu et al, Micromachines. 13, 291 (2022)
[3] Jayatilleka et al, Journal of Lightwave Technology. 39, 15 (2022)
[4] Milosevic et al, IEEE Journal Of Selected Topics In Quantum Electronics. 24, 4 (2018)
[5] Chen et al, Optics Express. 28, 12 (2020)
[6] Chen et al, Photonics Research. 5, 6 (2017)

Acknowledgments: EU Project DOLORES (101130178). Royal Society URF (UF150325).

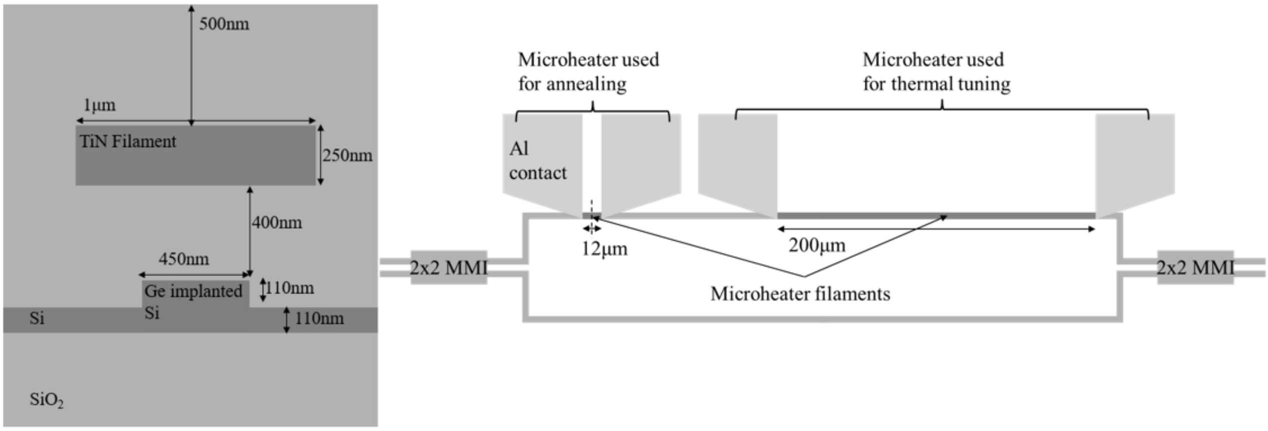

Figure 1. The cross-section (left) is taken at the dotted line on the diagram of the MZIs used in this work (right). The cross section is of a Ge ion implanted waveguide with a microheater filament above it. The MZI has two microheaters over its upper arm, the first is above a 12µm long implanted section of waveguide and is used for electrical annealing. The second (200µm) long microheater is above unimplanted waveguide and was used for thermal tuning.

Thresholds for the average phase change from the previous three voltage pulses, Δφ (radians)	The next voltage step (mV)
Δφ > 0.012	-1.2
0.012 > Δφ > 0.006	0
0.006 > Δφ > 0.001	0.6
0.001> Δφ	10

Table 1. Table displaying the thresholds for the average phase change brought about by the previous three voltage pulses that will determine what voltage step is taken next.

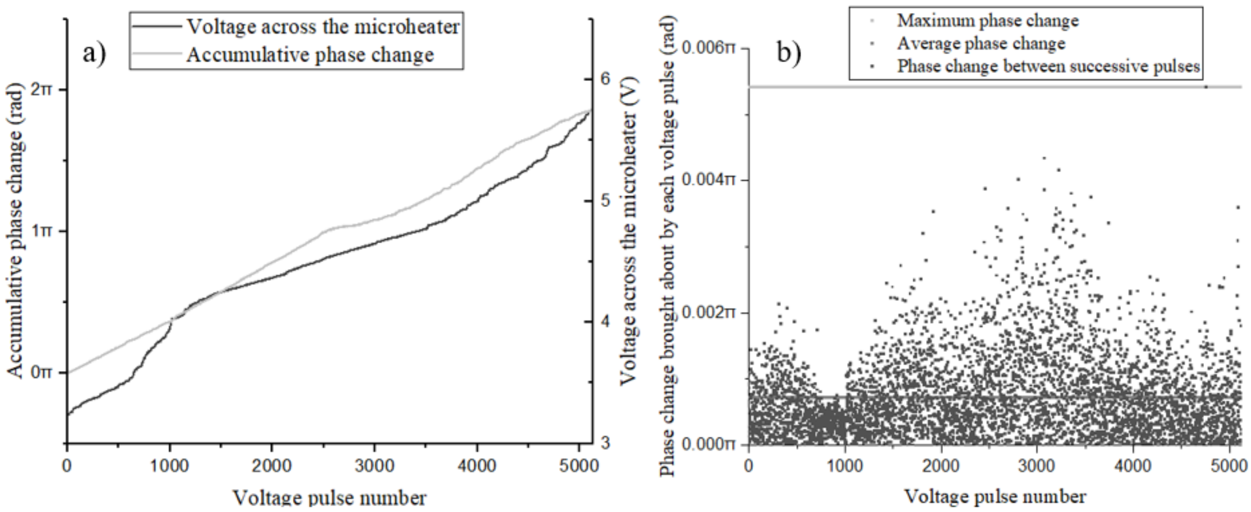

Figure 2. a) Graph showing the voltage being applied across the microheater (for electrical annealing) at each voltage pulse and the accumulative phase change being brought about by the annealing. **b)** Graph showing the phase change measured between successive pulses.