Integration of indium tin oxide on silicon for enabling electro-optical functionalities

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Abstract

ITO has since long been used for transparent electrodes in opto-electronic applications such as photovoltaics and display technology because of its transparency to visible and near-IR light. This transparency can also be exploited to integrate ITO on silicon waveguides for modulation and switching at the 1550 nm telecom wavelength. For wavelengths beyond 1 µm, ITO's permittivity can be described using a Drude model [1]. Since the plasma frequency of ITO is in the near-IR range, changes in the carrier density can lead to a refractive index shift greater than unity [2]. This strong manifestation of the plasma dispersion effect makes ITO so interesting for modulation. Until now, most proposed ITO-based absorption modulators used a MOS structure to accumulate charges capacitively and change the permittivity drastically in this layer. Since this layer is only a few nanometers long, very high confinement of the optical mode is needed to increase their interaction and reduce the structure's footprint. We have simulated structures for absorption modulation under the assumption that the bulk carrier density in the ITO can be tuned, for instance using P-N or N^+-N junctions. For P-N junctions, a transparent, degenerate p-type semiconductor is needed. Degenerately doped silicon and the new promising p-type transparent conducting oxide LaCuOSe are candidates. Mg-doped LaCuOSe is reported to reach a hole density of 2.10^{20} cm^{-3} with a relatively high hole mobility [3]. Under the assumption of complete depletion in the junctions, the absorption contrasts of our simulated absorptive modulators reach 200 for both polarizations. Refractive modulators based on P-N junctions have already been explored for silicon. However, the index shift due to the plasma dispersion effect can be up to two orders of magnitude larger in ITO than in silicon. Integration of ITO near the waveguide can lead to higher modal index modulation with a smaller device footprint. ITO's conducting properties also suggest its use as an efficient heater for thermo-optic switching. However, experiments have shown that dissipating power in the deposited ITO layers leads to nonlinear and irreversible changes in the optical properties of the waveguides (figure 1a: power through the ITO strip on the long arm of the MZI). A resonance shift has been observed when applying a voltage over the ITO (figure 1b). This shift is not reversed completely when the voltage returns to zero and thus a permanent change is induced. In contrast, the insertion losses of the structure are more reversible in this experiment (figure 1c: maximal and minimal signal value around the resonance). Although the optical properties of the waveguide are changed, the electrical properties of the ITO remain the same. Understanding the origin of this behaviour and controlling it would lead to ITO enabling non-volatile switching and furthermore might allow the tuning of the ITO integrated structures' optical response after deposition.

References

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Figures

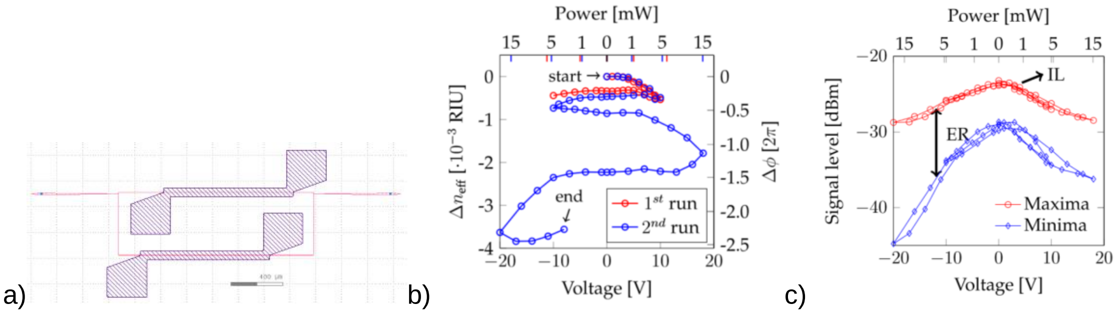

Figure 1: (a) ITO deposited onto an asymmetric MZI structure with TE gratings. Experimental change in (b) modal index, phase shift, (c) insertion loss and extinction ratio as function of the dissipated power in the ITO strip on the long arm of the MZI. Each measurement took 3 minutes to complete and was immediately followed by the next measurement.