SiP Waveguide-Embedded Electronic Devices controlled by Substrate/Gate Potential Tuning

(Student paper)

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Electrical properties of waveguide-embedded optoelectronic devices in Silicon Photonics chips are affected by the chip substrate potential, that can compensate the effect of electric charges in the cladding oxide. By properly tuning the substrate voltage, we demonstrate the control of a waveguide-embedded heater and the photoconductivity enhancement of a transparent photoconductor, that can be used to detect light intensities down to -60dBm.

Keywords: *silicon photonics, integrated photodetectors, substrate voltage tuning*

INTRODUCTION

The positive charges in the oxide surrounding a Silicon Photonic (SiP) waveguide (WG) and the trap energy states at the Si/SiO2 interface have influence on the electronic behaviour of WG-integrated devices. As reported in [1], these charges affect in particular the free-carrier concentration of low-doped WGs, that does not correspond anymore to the nominal doping value at fabrication (10^{15} cm^{-3}, p-doped), and degrade the electrical conductivity of their core.

Figure 1a illustrates the cross-section of the device we studied in this work, fabricated in a commercial SiP technology. The device is embedded in a rib-waveguide with 500 x 220 nm core, 900 x 90 nm slabs and a total length of 100 µm. The device has been designed with a p-i-p structure: the silicon waveguide (WG) core and the optical slabs have the same 10^{15} cm^{-3} p-type doping of the original SOI wafer, while the external slab regions (named Drain and Source) are heavily p-doped (10^{20} cm^{-3}) to ensure ohmic electrical contacts. The 900 nm distance of the electrical contacts from the WG core guarantees that no additional propagation losses are introduced. The box oxide is 3 µm thick. As we demonstrated in [1], the device tends to be naturally depleted from free carriers due to the effect of oxide charges, thus showing a transversal resistance (between V_S and V_d terminals in the figure) that is about four orders of magnitude higher (GΩ) than what expected from the doping level (tens of kΩ) if surface phenomena are not considered.

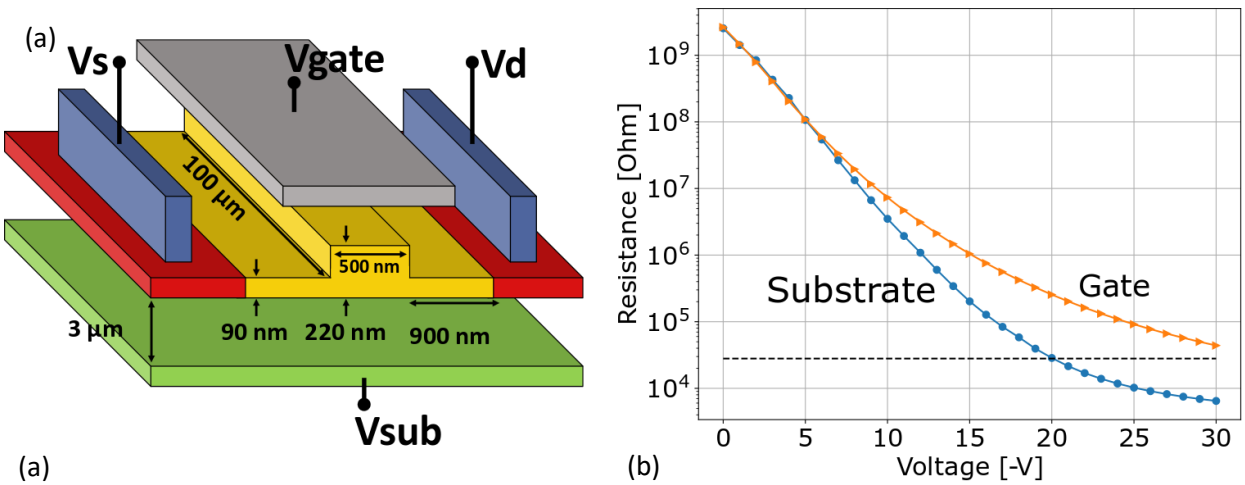

Figure 1: a) Schematic structure of the measured device. b) Measured resistance as function of the control voltage applied to the Gate electrode (orange) or to the chip substrate (blue).

However, the surface effects can be compensated by applying a voltage to the chip substrate or to a gate electrode placed over the waveguide by using one of the available metal layers of the technology. Fig. 1b shows how the device resistance can be tuned by the substrate/gate potential. When V_{SUB} is around -20V the effect of oxide charges

is compensated and the device resistance is brought back to its nominal value (28kΩ). The control over the effect of oxide charges by means of an external potential is of fundamental importance to tune and set the free carrier concentration of the WG core to the desired level. In this way, we can not only operate the WG-embedded electronic devices in their optimal working point, but also conceive new functionalities of interest.

HEATER WITH LINEAR BEHAVIOUR

Heaters actuators are commonly used to control the behaviour of SiP fabrics. They are resistances placed close to the WG or embedded in it [2], driven by an external voltage. When power is dissipated through the heater, the local temperature increases, modifying the WG effective refractive index (n_{eff}) according to the thermo-optic coefficient of silicon. The quadratic dependence of the controlled quantity (n_{eff}) on the control variable (heater voltage) can be problematic when using the heater as actuator in a feedback loop to lock the working point of photonic structures, like Mach-Zehnder interferometers or ring-resonators. Instead, by taking advantage of the relation between the WG resistance and substrate voltage [1], it is possible to have a linear dependence between the new control variable (V_{SUB}) and n_{eff}. This is well demonstrated by the experiments in Fig.2. The figure shows the linear variation of the resonance peak of a ring resonator as a function of the substrate potential when a constant voltage (V_{ds} = 12V) is applied across the device. The figure also reports the quadratic behaviour that is obtained when the actuator is operated in the standard way.

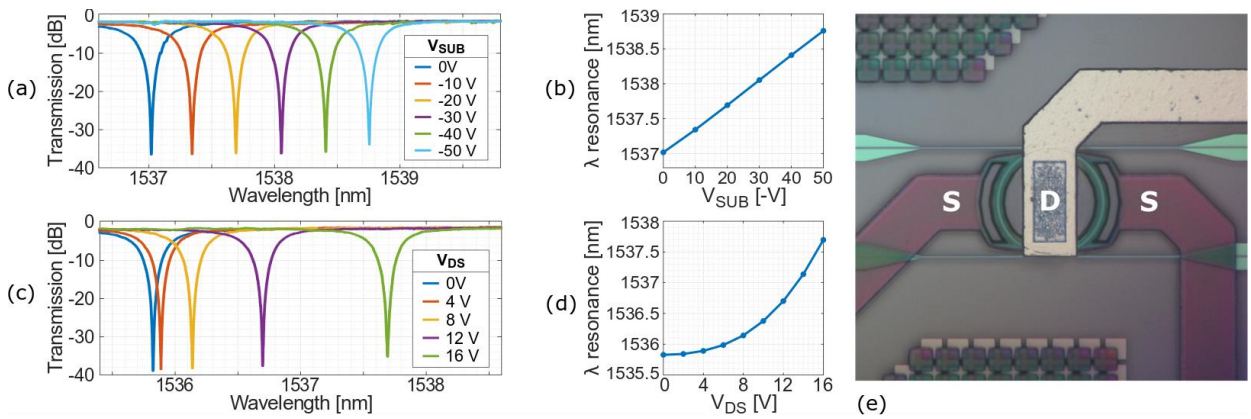

Fig. 2. a) Transfer function of a ring resonator for different values of the substrate voltage (V_{ds} = 12V). b) Linear variation of the resonance wavelength of the microring resonator as a function of the substrate voltage. c) Transfer function of the ring resonator for different values of V_{ds} voltage (V_{sub} = -20V). d) Quadratic dependence between the resonance peaks and the voltage applied across the device. e) Microscope photograph of the device.

PHOTOCONDUCTOR SENSITIVITY ENHANCEMENT

Oxide charges greatly affect the performance of the p-i-p device also when used as in-line photoconductor [3]. Indeed, the WG depletion causes an oddly distributed electric field in the WG core and induces longer transit times and smaller photoresistive gains [4] for the photo-generated carriers. Compensation of this effect is therefore essential. Figure 3a shows the variation of photo-current obtained by tuning the substrate voltage from 0V to -30V. The photo-generated current is greatly amplified as the substrate voltage goes negative. Thanks to this amplification, light intensities as low as -60dBm can be easily measured with a standard electronic readout. To highlight the extraordinary performance that can be achieved with a low doped photoconductor, we have compared it with a commonly doped device [5] and with a p-i-n photodiode. The three devices differ just for the doping type and level of WG and slab regions while they all have the same geometry. The doped photoconductor has a n^+-n-n^+ structure: n^+-doped slabs with a doping concentration of 10^{20} cm^{-3} and n-doped core with a doping concentration of 10^{17} cm^{-3}, leading to a resistance around 60Ω. Its sensitivity curve is shown in Fig. 3a in green at the same V_{ds} voltage of 1V. It is clearly seen that the produced photocurrent is lower by more than one order of magnitude with respect to the low-doped device, thus resulting in a light intensity detection capability limited to about -35 dBm. The same figure also reports the photodiode sensitivity as a reference for the primary current (red) directly generated in the WG without the amplification mechanism of the photoconductors.

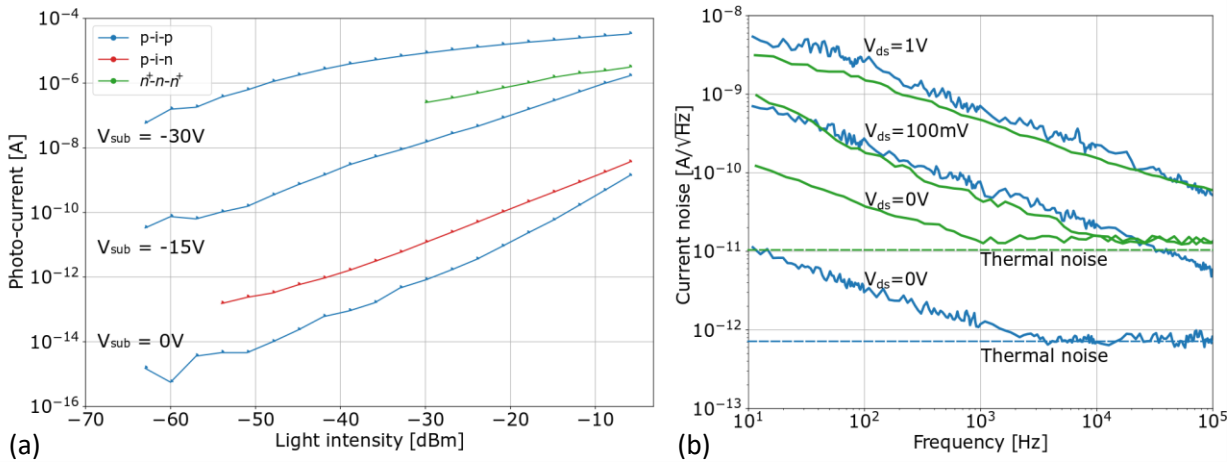

Fig. 3. a) Photo-generated current for the three measured WG-embedded sensors. The sensitivity curve of the low doped photoconductor (blue curves) varies with the substrate voltage, while that of the doped photoconductor (green) and the p-i-n photodiode (red) does not depend on it. b) Current noise power spectral densities of the two photoconductors when V_{ds} is 0V, 100mV and 1V, revealing a bias dependent 1/ f component (V_{sub} = -30V for the low-doped device).

PHOTOCONDUCTOR NOISE

As a final aspect in the comparison between the two types of photoconductor, their noise behaviour has been investigated. Figure 3b shows the current noise power spectral density measured at V_{ds} bias voltages of 0V, 100mV and 1V in both devices [6]. The measurements confirm that, when V_{ds}=0V, the noise of both photoconductors agrees with their thermal noises, with the low-doped device showing a much lower current noise than the high-doped one, in proportion to their resistances (the residual 1/f noise measured at very low frequencies is in this case attributed to the measuring instrument). However, as soon as the devices are biased, they both show an unexpected yet comparable bias-dependent 1/f component. This 1/f component follows Hooge's law [7] and the corner frequency is proportional to the square of the current in the device. Because of this, the two photoconductors are equivalent in terms of noise when operated at the same bias voltage, unless a readout frequency larger than the noise corner of the doped device is targeted. The better performance in terms of sensitivity of the low-doped sensor should thus be attributed only to its higher photoconductive gain.

CONCLUSIONS

We demonstrated that oxide charges can impair the behaviour of waveguide-embedded electronic devices and showed how to compensate their effect by properly acting on the voltage of the chip substrate or by using a gate electrode. As two applications, we reported the use of the substrate/gate voltage to linearly change the power dissipation of a waveguide-embedded heater and enhance the photoconductivity of transparent photoconductors. To demonstrate the effectiveness of this approach, the performance of the obtained sensor has been compared to other transparent detectors, showing a much better sensitivity (-60 dbm) and the same noise behaviour.

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