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

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***Abstract*—The substrate potential in SiP chips define the electrical properties of waveguide-integrated optoelectronic devices by counteracting the depletion of free carriers caused by oxide charges. Heater control and photoconductivity enhancement by orders of magnitude by means of substrate potential tuning is demonstrated.**

I. Effect of the substrate voltage

The positive charges present in the bulk oxide surrounding a Silicon Waveguide (WG) in SiP technology and the trap energy states at the Si/SiO_2 interface can impair the electronic behaviour of WG-integrated devices. As reported in [1], these charges especially affect the free-carrier concentration of low-doped WGs, that does not correspond anymore to the nominal doping value at fabrication (intrinsic, $10^{15} cm^{-3}$ p-doped), and degrade the electrical conductivity of their core.

Fig.1 shows this effect measured on the transversal resistance of a p-i-p device embedded in a rib-WG with a $500nm \times 220nm$ intrinsic core and $900nm \times 90nm$ p-doped ($10^{19} cm^{-3}$) slabs. The transversal resistance (between Vs and Vd terminals in the figure) is about four orders of magnitude higher ($G\Omega$) than what expected from the doping level (tens of $k\Omega$) if oxide phenomena are not taken into account. However, the surface effects can be counteracted by applying a proper voltage to the chip substrate. In particular, Fig. 1 shows that when V_{sub} is around $-20V$ the effect of oxide charges is compensated and the device resistance is brought back to its nominal value ($28k\Omega$).

The control over the effect of oxide charges by means of an external potential, in this case the substrate voltage, is of fundamental importance to tune and set the free carrier concentration of the WG core at the desired level. In this way, we can not only operate the WG-embedded electronic devices in their optimal working point, thus improving their performance, but also conceive new functionalities of interest, as in the following.

II. 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.

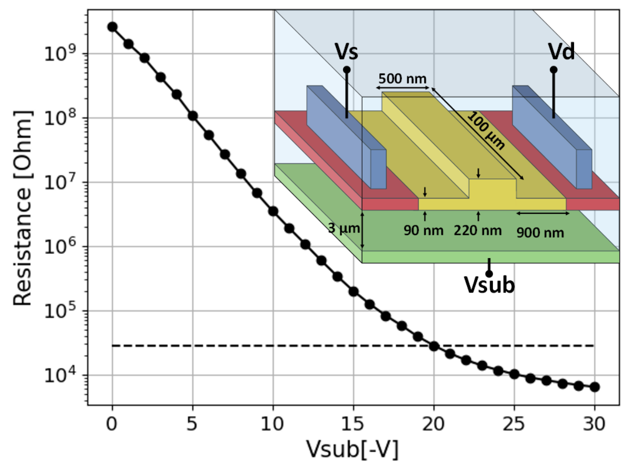

Fig. 1. Transversal resistance of a p-i-p waveguide-embedded device (geometrical dimensions in the inlet, not to scale) as a function of the substrate voltage. The WG core (yellow) is lightly doped ($10^{15} cm^{-3}$ p-type) while lateral ohmic contacts (red) are strongly p-doped ($10^{19} cm^{-3}$) to ensure Ohmic contacts. The WG is surrounded by $3\mu m$ thick oxide containing fixed positive charges in the volume and trap energy states at the interface with silicon. By acting on the substrate voltage it is possible to control the oxide charge effect and restore the nominal $28k\Omega$ device resistance value.

The quadratic dependence of the controlled quantity (Δn_{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 WG resistance and substrate voltage [1], it is possible to have a linear dependence between the new control variable (V_{sub}) and Δn_{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 voltage when a constant voltage ($V_{ds} = 12V$) is applied across the device. The figure also reports the quadratic behaviour that would be obtained in the standard operation of the heater.

III. Photo-resistor sensitivity enhancement

Oxide charges greatly affect the performance of the p-i-p device also when used as in-line photo-resistor, since the

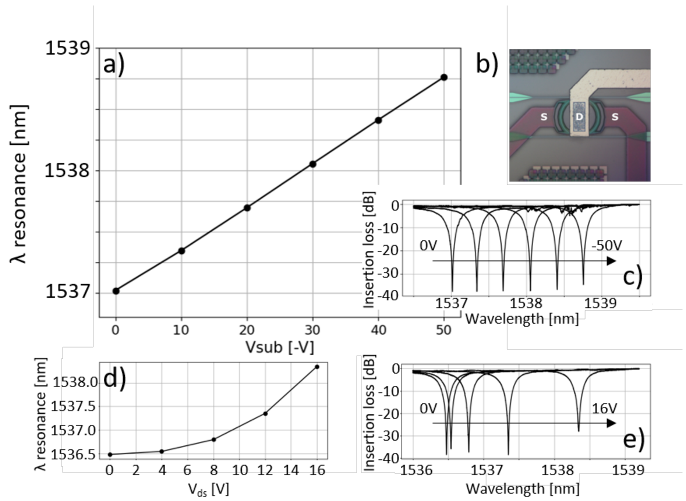

Fig. 2. a) Linear dependence of the resonance peak of the b) micro ring resonator as a function of the substrate voltage and c) corresponding transfer functions of the ring (through-port) for different substrate voltages. d) Quadratic dependence between the resonance peaks and the voltage applied across the device and e) corresponding transfer functions for different V_{ds}.

WG depletion causes a oddly distributed electric field in the core and induces longer transit times for the photo-generated carriers. Compensation of this effect is therefore essential. Figure 3 shows the variation of photo-current obtained by tuning the substrate voltage from $0V$ to $-30V$: when V_{sub} reaches $-30V$, an increase of a factor between 10^4 and 10^6 is measured with respect to the case of zero substrate bias. Thanks to this amplification, a signal in the μA range is produced even for light intensities as low as $-60dBm$. This current is comparable or even larger than what can be obtained with a standard highly doped photo-resistor [3] while the detector noise is lower, since the higher dark resistance produces lower thermal noise [4]. The signal-to-noise ratio of the measurement is thus greatly improved. In addition, this level of performance is reached without doping the core, allowing minimum propagation losses in the WG.

IV. Charge compensation with local gate device

The oxide charges compensation by means of substrate potential inevitably controls all the electronic devices in the chip. In view of single device tuning and calibration, we have experimentally verified that all the previous results, obtained by applying a voltage to the chip substrate, can be achieved also by using a small metal 'Gate' electrode placed over the WG at the site of the single device, enabling a truly local control. Figure 4 shows the cross section of the previous p-i-p structure with the addition of the Gate and illustrates the electrostatic compensation of charges. The figure also reports the experimental control of the heater current by the Gate potential (on the left) and the enhancement of the photo-generated current in the photoconductor device (on the right). Control by local Gate is at zero static power consumption and its implementation over a large number of devices in a SiP fabric is under development.

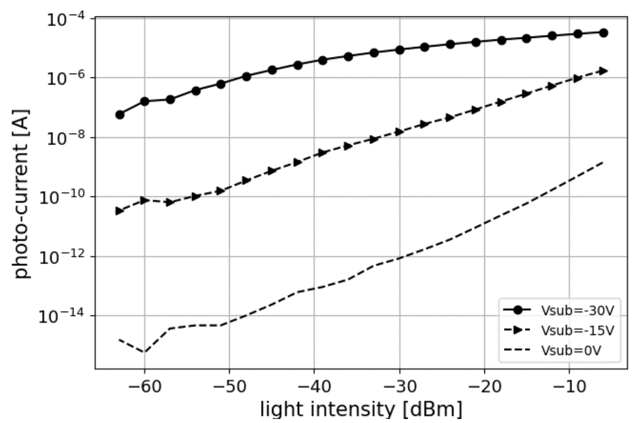

Fig. 3. Effect of the substrate voltage on the sensitivity of the p-i-p photoconductor as a function of light intensity, for $V_{ds} = 1V$. As the substrate voltage decreases, the resistance of the device decreases and the photo-current increases.

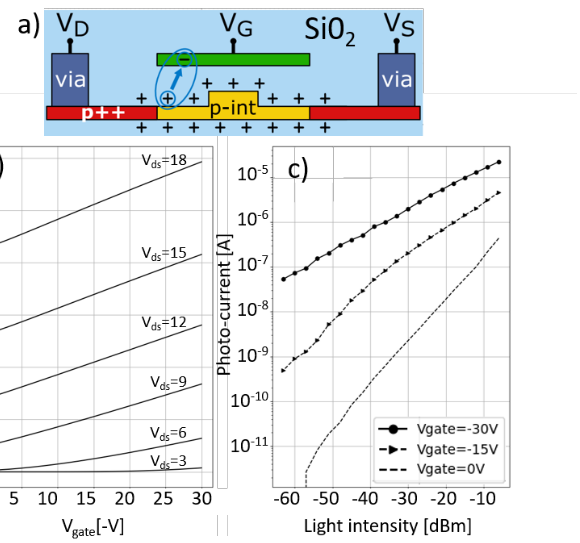

Fig. 4. a) Cross-section of the p-i-p device with a gate electrode placed over the WG core. A negative voltage applied to the gate enables local oxide charge compensation and WG free carriers recovery. b) Local heater current modulation as function of the gate voltage and c) photoconductor sensitivity enhancement for 3 values of gate voltage, at $V_{ds} = 5V$.

The work has been developed within the EU projects NEBULA (G.n.871658) and SUPERPIXELS (G.n.829116).

References

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