An integrated optical link in 140 nm SOI technology

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Abstract: A silicon-on-insulator based optical link is introduced. Higher opto-coupling efficiency and temperature-resilience are obtained via avalanche-mode light-emitting diode operation against forward-mode operation. Self-heating induced thermo-coupling in steady-state is de-embedded by calibrating the photo-detector's photovoltaic characteristics.
OCIS codes: (040.6040) Silicon; (130.0250) Optoelectronics; (230.3670) Light-emitting diodes; (230.5170) Photodiodes; (130.0130) Integrated optics; (040.1880) Detection; (120.6810) Thermal effects.

1. Problem statement, motivation and method:

Intra-chip optical interconnects offer high speed data transfer [1] with very small form factor. The viability of such a CMOS-integrated optical link in Silicon (Si) demands a good coupling efficiency together with proper galvanic isolation. Avalanche-mode light-emitting diodes (AMLEDs) serve the first requirement as light sources [2], because of the significant overlap between their electro-luminescence (EL) spectra and the spectral responsivity of Si photo-diodes (PDs) [3], in contrast to the same system with a forward-mode (FM) LED. The second criterion can be fulfilled using Si-on-insulator (SOI) process. Prior art [4,5] report opto-coupling in a 0.35 µm bulk process that lacks galvanic isolation, implying higher electrical crosstalk and poorer isolation voltage. However, owing to a higher electrical power dissipation (P) and, consequently, self-heating in AMLEDs, coupling through such a link to a PD is a mix of fast optical transmission and slow thermal conduction. Therefore, it is needed to resolve these two components, which are entwined in steady-state or low-frequency operation. The LED and PD are realized with vertical n^+p junctions in a 0.14 µm SOI technology (Fig. 1(a), (d)). Galvanic isolation in the link is realized with medium trench isolation (MTI); the opto-coupling is via shallow trench isolation (STI). The opto-coupling quantum efficiency is defined as the ratio of the short-circuit current (I_{SC}) of the PD, and the LED current (I). I_{SC} depends on the optical intensity (L) of the LED and absorption coefficient (α) of the PD (that increases with junction temperature, T_j [6]). The open-circuit voltage (V_{OC}) and the I_{SC} of the PD are calibrated using an off-chip reference red LED (~650 nm), at well-defined ambient temperatures (T), yielding their exclusive dependencies on T_j and L. V_{OC} can be expressed as [7],

$$V_{OC}(L,T_j) = \left(\frac{kT_j}{q}\right)\ln\left(1+\frac{I_{SC}(L,\alpha(\lambda,T_j))}{I_0(T_j)}\right), \quad (1)$$

where I_0 is the dark current, and λ is the photon-wavelength. Further, $T_j = T+\Delta T = T+P\cdot R_{TH}$, where R_{TH} is the effective thermal resistance of the system. In the AMLED, ΔT is mainly caused by self-heating because of its relatively high $P=P_{AM}$ (~0.13 W). The calibrated curves are used to estimate ΔT in the PD by mapping the deviation in V_{OC} for AM from the calibrated curve (fitted to Eq. (1)) onto the V_{OC}-T_j curve. A subsequent mapping of ΔT onto the I_{SC}-T_j curve yields the component of I_{SC} caused by the self-heating (SH)-induced rise in $\alpha(T)$, and is denoted here by $\Delta I_{SC}^{(SH)}$. Thus, the contributions of L, and α, to the PD-current are decoupled. The same I_{SC} at 300 K for both (the AMLED and off-chip LED) is established for this calculation to ensure the same light absorption in the PD irrespective of the λ-dependency of α.

2. Results and Conclusions

Photon emission peaks in the visible and infra-red (IR) range for the AMLED and the FMLED respectively (Fig. 1(e), (f)). The EL-micrographs are shown in Fig. 1(b) and (c), respectively. In AMLED operation, $|I_{SC}|$ increases proportionally with I and hence with L [8]. However, V_{OC} initially increases and then decreases for higher values of I (Fig. 1(g)), signifying a thermal effect, which is negligible for the FMLED (Fig. 1(h)) since $P_{FM} << P_{AM}$). Fig. 2 outlines the aforesaid technique to extract ΔT. Calibration with the off-chip LED shows that an increase in only L (at a fixed T), results in an increase in both $|I_{SC}|$ (Fig. 2(a)) and V_{OC} (Fig. 2(b)). For higher T (and fixed L), V_{OC} decreases (Fig. 2(c)) while $|I_{SC}|$ moderately increases, as α increases (Fig. 2(d)). Owing to higher α at shorter λ, a ~7.5 times higher coupling efficiency and a 5 times reduction in temperature coefficient of I_{SC} are obtained in AM as compared to FM at the same I (=4 mA) for a link spacing of 28 µm (Fig. 3(a), Table 1). Post de-embedding, ΔT values of up to ~50 K were extracted for AMLED operation, with a strong dependency on I (Fig. 3(b)). Fig. 3(c) shows the separated components (~87% opto-coupling, ~13% thermo-coupling) of the sensed I_{SC}. To conclude, wide-spectrum opto-coupling in 0.14 µm SOI technology is achieved for the first time. AMLED self-heating adds a thermal data path to the fast optical path, which is de-embedded using our proposed technique. The design is suitable for smart-power applications e.g. level shifters.

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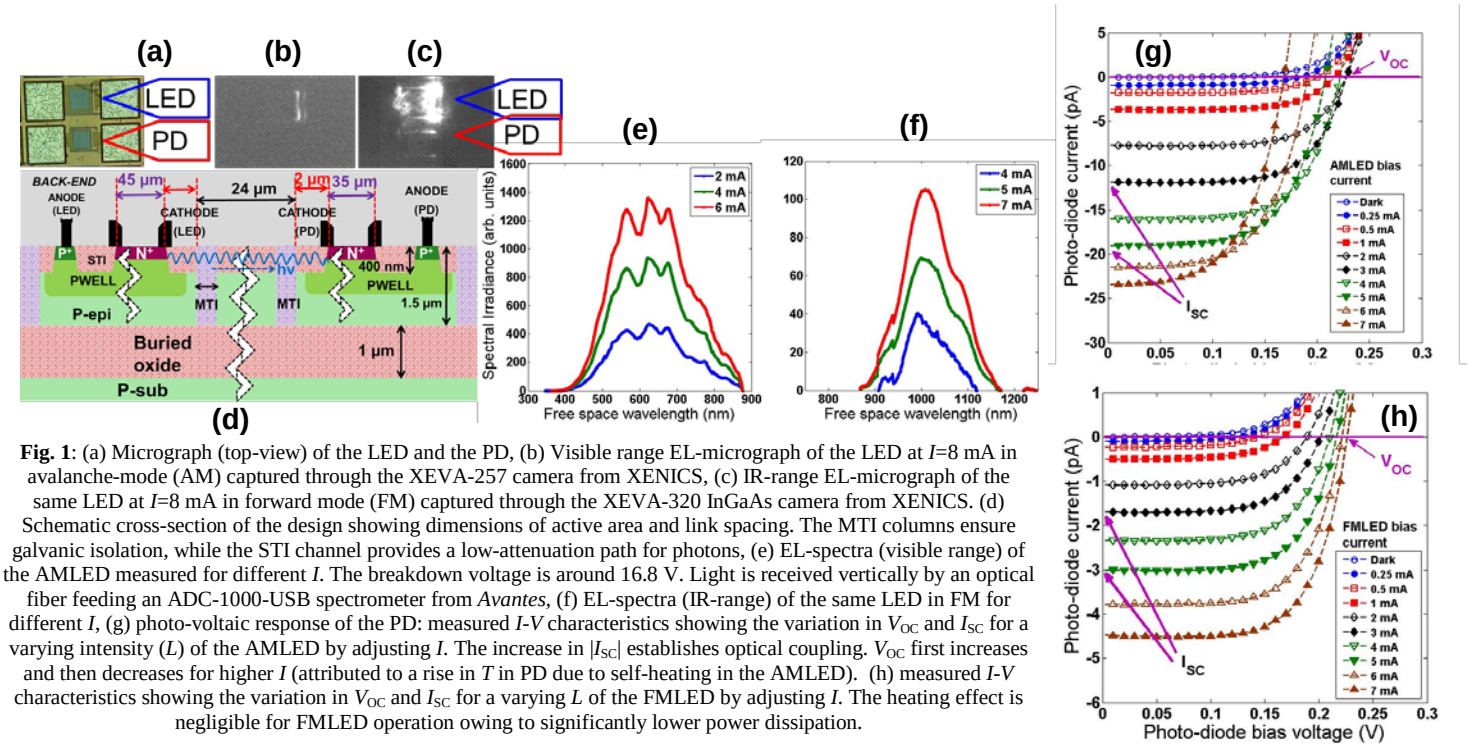

Fig. 1: (a) Micrograph (top-view) of the LED and the PD, (b) Visible range EL-micrograph of the LED at I=8 mA in avalanche-mode (AM) captured through the XEVA-257 camera from XENICS, (c) IR-range EL-micrograph of the same LED at I=8 mA in forward mode (FM) captured through the XEVA-320 InGaAs camera from XENICS. (d) Schematic cross-section of the design showing dimensions of active area and link spacing. The MTI columns ensure galvanic isolation, while the STI channel provides a low-attenuation path for photons, (e) EL-spectra (visible range) of the AMLED measured for different I. The breakdown voltage is around 16.8 V. Light is received vertically by an optical fiber feeding an ADC-1000-USB spectrometer from *Avantes*, (f) EL-spectra (IR-range) of the same LED in FM for different I, (g) photo-voltaic response of the PD: measured I-V characteristics showing the variation in V_{OC} and I_{SC} for a varying intensity (L) of the AMLED by adjusting I. The increase in $|I_{SC}|$ establishes optical coupling. V_{OC} first increases and then decreases for higher I (attributed to a rise in T in PD due to self-heating in the AMLED). (h) measured I-V characteristics showing the variation in V_{OC} and I_{SC} for a varying L of the FMLED by adjusting I. The heating effect is negligible for FMLED operation owing to significantly lower power dissipation.

Table 1: Key steady-state FOMs of the opto-coupler. Values are reported at T=300 K, I_{LED}= 4 mA, PD dark current of ~10 fA, and a link spacing of 28 µm.

FOM	Coupling via AMLED	Coupling via FMLED
EL-spectrum	400-870 nm	900-1150 nm
Minimum LED supply voltage	Breakdown voltage (16.8 V)	0.7 V
Opto-coupling quantum efficiency: $\Delta I_{SC}/I_{LED}$	AMCE: 3.75 x 10^{-9}	FMCE: 0.5 x 10^{-9}
Opto-coupling power efficiency: $(\Delta I_{SC} \cdot V_{OC})/ P_{LED}$	3.60 x 10^{-11}	9.46 x 10^{-11}
Heating in the PD: ΔT	18 K	Negligible
Effective thermal resistance: R_{TH}	192.47 K W^{-1}	---
Temperature coefficient of I_{SC}: $\Delta I_{SC}/(I_{SC}(T) \cdot \Delta T)$	0.5 % K^{-1}	2.6 % K^{-1}

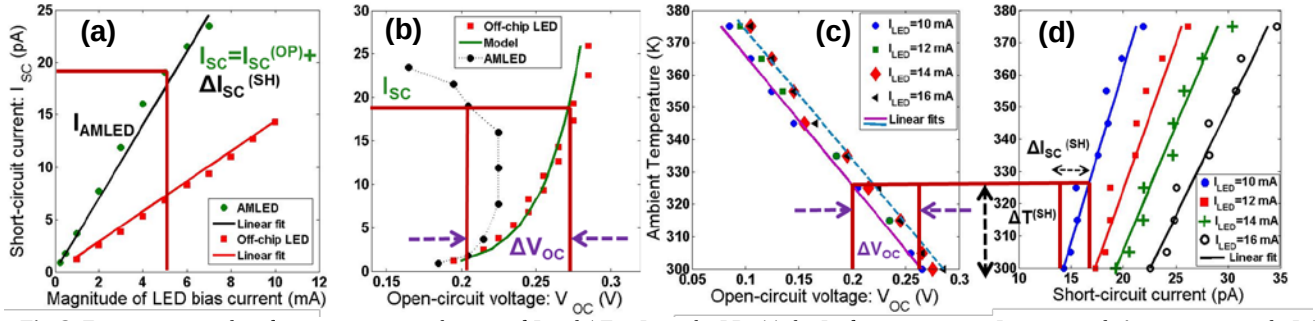

Fig. 2: Extraction procedure for separating contributions of L and ΔT to I_{SC} in the PD: (a) the I_{SC} for a given input I is measured. An increase in only L (at a fixed T=300 K) (*red*) results in an increase in $|I_{SC}|$. (b) The corresponding deviation in the measured avalanche-mode V_{OC} (*black*) from the calibrated value (using the off-chip LED at 300 K and modeled via Eq. 1 (*green*)) is recorded. Note that an increase in only L (*red symbols*) results in an increase in V_{OC}. Next, (c) ΔT is calculated from the calibrated gradient of V_{OC}-T curve of the PD. A rise in only T (for a fixed L) leads to a decrease in V_{OC} with a mean temperature coefficient of -2.5 mV K^{-1}. Finally, (d) the rise in I_{SC} due to the thermally induced rise in α is calculated by mapping the obtained ΔT onto the calibrated gradient of I_{SC}-T curve. Note that a rise in only T (for a fixed L) leads to a moderate increase in $|I_{SC}|$ with a mean temperature coefficient of 0.12 pA K^{-1}.

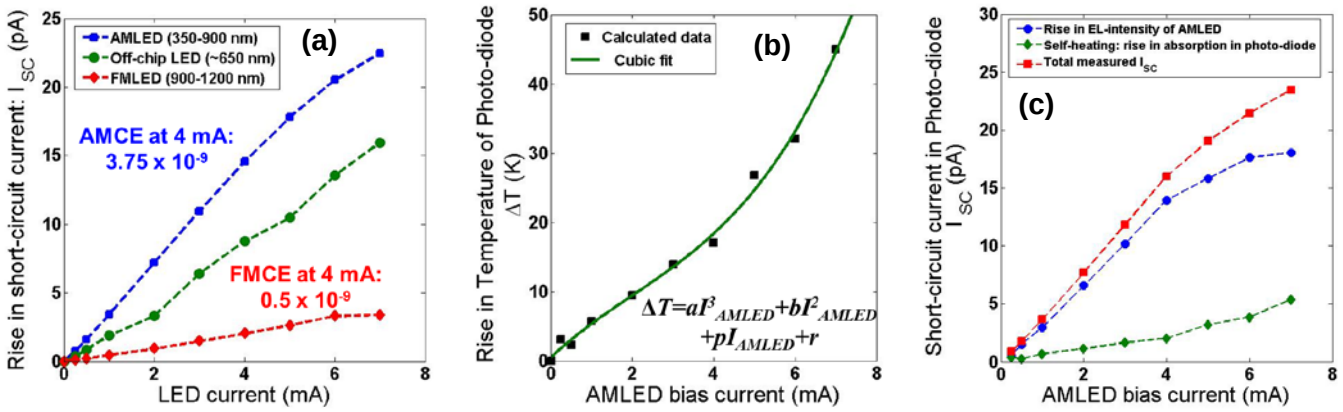

Fig. 3: (a) Measured I_{SC} in the PD plotted against I for the AMLED (*blue*), FMLED (*red*) and off-chip LED (*green*). Prior to any de-embedding, the coupling efficiency is ~7.5 times higher for AMLED operation as compared to FMLED operation. (b) Calculated rise in temperature (*symbols*) in the PD owing to self-heating in the AMLED, following the technique in Fig. 2. The values are fitted to the shown polynomial function where a=1.2 x 10^8 A^{-3} K, b=-7.3 x 10^5 A^{-2} K, p=5.4 x 10^3 A^{-1} K. The residue r (0.56 K) should be ideally zero (indicating no heating for zero current), and hence it is an indicator of goodness-of-fit of the model. (c) Resolved components of the measured I_{SC} (*red*) for AMLED operation against I: $I_{SC}=I_{SC}^{(OP)}+\Delta I_{SC}^{(SH)}$, where $I_{SC}^{(OP)}$ (*blue*) is the sole contribution of L of the AMLED, while $\Delta I_{SC}^{(SH)}$ (*green*) is the contribution of increased α due to heating at a given AMLED bias point. 87% optical and 13% thermal coupling is obtained through the 28 µm link.