Avalanche-mode Si light-emitting transistor for narrow-band emission near 760 nm

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Abstract

We report an avalanche-mode light-emitting transistor (AMLET) in silicon (Si), based on a lateral bipolar junction, which emits light near 760 nm optical wavelength with a record low bandwidth of 38 nm. The AMLET, designed in a CMOS-compatible silicon-on-insulator (SOI) photonics platform, is optically confined within a 0.21 μm thick SOI layer, which forms a Fabry-Perot (FP) resonator perpendicular to the Si surface. Light is emitted from the reverse biased emitter-base junction via phonon-assisted hot carrier recombination and, additionally, minority carriers are injected via the forward-biased Base-Collector junction. The combination of injection from collector terminal through a narrow base and FP optical resonance, yields a high optical power efficiency of 4.3×10^{-6} at VBC = 0.8 V and VEB = 10 V. Our work opens new possibilities in spectralengineering of Si light-emitters, which could boost performance of all-Si optical interconnects and sensors.
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Index Terms—Avalanche breakdown, electroluminescence, Fabry-Pérot resonance, integrated optics, silicon.

I. INTRODUCTION

Silicon (Si) p-n junctions exhibit broad-band electroluminescence (EL) at wavelengths $\lambda \sim 400$–900 nm when operated in avalanche-mode (AM), with low efficiencies [1]–[4]. Driven by the success of CMOS technology, the advent of Si photonics, and a growing demand for increased on-chip functionality, research on Si light-sources has gained attention [5]–[12]. The AM-EL of Si has a significant spectral overlap with the responsivity of Si photodiodes [7], [13], with the range of human vision [14], and with the absorption spectrum of various biochemical entities [15], [16]. As such, despite the low optical power efficiency ($\eta_{opt} \sim 10^{-6}$), AM Si LEDs have successfully emerged as light-sources in monolithic optical interconnects [5], [8], [17], pigment sensors [18], and CMOS micro-displays [11]. The performance metrics in such end-applications, e.g. energy consumption per bit [8], [19] and sensor detection threshold [20]–[22], benefit from an increased $\eta_{opt}$ in a wavelength-range of interest.

Aided by several commercially available CMOS technologies, significant efforts have been made to increase $\eta_{opt}$ and to stimulate the AM EL-intensity in a narrow bandwidth. These include carrier injection in a 3-terminal device [4], carrier energy and momentum engineering [23], [24], increasing field-profile uniformity via superjunction LEDs [25], and gated FET-based LEDs [11], [26]. Here, we present an avalanche-mode light-emitting transistor (AMLET) fabricated in a CMOS-compatible Si-photonics platform, that implements the electronic functionality of a lateral bipolar junction (inspired by [4], [28]) within an optically confined SOI-cavity, to enhance AM EL within a record-low bandwidth and high $\eta_{opt}$.

II. RESULTS AND DISCUSSION

The AMLET design consists of a lateral n-p-n bipolar junction with symmetrically doped emitter (E), base (B) and collector (C) regions. The base length is 1.0 μm, while the total device length is 21.0 μm (Fig. 1(a)). Two n-p-n device units are connected in parallel with a shared base electrode. Highly doped n+/p+ implants form ohmic contacts to bond
orders of magnitude. The same trend is obtained using TCAD doping levels of $4 \times 10^{-17}$ cm$^{-3}$ are simulated along the x-axis (1-D) assuming a uniform ε obtained by integrating the AM EL spectral irradiance. The biased, respectively, under a fixed voltage bias and a fixed the E-B junction set in AM. The E and C terminals were at 298 K in common-base configuration (Fig. 1(d)) with 20 s integration time. We observe that high injection of carrier multiplication.

The AMLET was measured in continuous dc-operation at 298 K in common-base configuration (Fig. 1(d)) with the E-B junction set in AM. The E and C terminals were biased, respectively, under a fixed voltage bias and a fixed current bias via a Keysight B2912A precision SMU. The AM EL spectral irradiance ε(λ) was measured by mounting a lensed multi-mode optical fiber pigtal of an LWP lightwave probe vertically. The LWP probe was fed to an AvaSpec ULS2048CL-EVO spectrometer. Total optical power $P_{\text{opt}}$ was obtained by integrating $\varepsilon(\lambda)$ over the $\lambda$-range 450–1000 nm and calibrating $\varepsilon$ at a given $\lambda$ using an AvaLight-DH-S-BAL light-source and a ThorLabs S155C photoreceiver (connected to PM100 power meter). Figs. 1(e), (f) show, respectively, the top-view die micrograph and the AM EL micrographs of the AMLET for both low and high injection from the B-C junction, measured vertically. Prior reported AM EL-spectra from 2-terminal [25] (grey) and 3-terminal [11] (blue) LEDs in Si CMOS technologies are shown for comparison. (Inset): Calculated spectral transmission coefficient of a 1-D Si Fabry-Pérot resonator (etalon) surrounded by SiO$_2$ showing a resonance at 784 nm coinciding with the AMLET EL-intensity peak. (b) Schematic E-k diagram of Si illustrating possible pathways for electron transitions that contribute to photon emission. The grey regions indicate the schematic energy ranges of hot carrier distributions reported in [24], [36].

For optical measurements, we set $V_{\text{EB}}>V_{\text{BR}}$ (Fig. 1(d)). The E-B junction emits light (Fig. 1(f)), at $I_{E}=1$ mA, for an carrier recombination lifetime of 2.5 ns. The discrepancies between TCAD and experiments are likely due to non-uniform doping depth-profiles in the experimental material, which could activate a parasitic transistor in parallel [31], as can be noticed from the kink in the forward biased $I_{C}$-$V_{BC}$ characteristics (Fig. 2(b)) at $V_{BC} \approx 0.6$ V, showing a ~10 times higher measured current at low injection compared with TCAD. $V_{\text{BR}}$ decreases (from 10 V to 8 V in experiment) with decreasing $V_{BC}$, indicating a clear injection-level dependency of carrier multiplication.
increasing $V_{BC}$ in steps from 0 to 1 V. The AMLET operation is governed by field-driven impact ionization in the E-B junction and carrier injection via diffusion current through the narrow base. For $V_{BC} \leq 0.7$ V, injection from the B-C junction is low, as shown in Fig. 3(a). Hot electrons (holes) generated in the E-B junction due to avalanche multiplication are swept to the emitter (base) by the high electric field (see Fig. 1(c)). The net $I_B$ flows out of the terminal: only a small fraction of holes are injected into the collector due to the forward bias $V_{BC}$. For $V_{BC} > 0.7$ V (high injection from the B-C junction), a higher fraction of generated hot holes can transit through the narrow base and cross the B-C junction potential barrier, leading to a reversal in the direction of net $I_B$ (see Fig. 3(b)). Similarly, cool electrons injected from the collector can diffuse through the narrow base and enter the E-B space charge region to contribute to avalanche multiplication at a lower $V_{EB}$ (see corresponding TCAD results in Fig. 3). Thus, the likelihood of both hot electrons and hot holes to be coincident is reduced. It is expected that recombination between either hot electrons with cool holes or cool electrons with hot holes near the E-B junction will be more likely and lead to photon-emission with energies in the range $1.5-1.7$ eV ($\lambda \sim 700-800$ nm), as predicted in [24].

Figure 4(a) shows the measured $\varepsilon(\lambda)$ of the AMLET, where the intensities are normalized by setting $\int \varepsilon(\lambda) d\lambda = 1$. Effect of varying $V_{BC}$ on $\varepsilon(\lambda)$ is negligible, indicating no effect on carrier energy distributions. We observe three important spectral bands: the yellow (Y)-band near $\lambda \approx 600$ nm, red (R)-band near $\lambda \approx 764$ nm and near-infrared (NIR) band near $\lambda \approx 850$ nm. Fig. 4(b) shows the Si energy dispersion curve (E-k diagram) with possible electron energy transitions used to explain the observed EL. Photon emission in the R-band (photon energies near 1.6 eV) is attributed to phonon-assisted recombination between hot electrons and holes (transition ‘B’ in Fig. 4(b)). The Y- and NIR band are attributed to other processes [24]. The peak intensity in the R-band is 2 times higher than that of the Y or NIR bands, and the FWHM of the R-band peak is only 38 nm (i.e. quality factor of 20). Such a spectral enhancement is significantly higher than that in prior reported Si AMLEDs [11], [24], [25], [32] (see Fig. 4). Further, the FWHM is, till date, the smallest reported for Si AM light-emitting devices.

The observed $\varepsilon(\lambda)$ depends on both electronic transitions and the optical mode density, and can be attributed to two factors. Firstly, our AMLET design favours photon emission in the R-band as discussed earlier. Secondly, the active Si cavity forms a lossy Fabry-Pérot resonator (etalon) [33] along z-axis. Considering the $\lambda$-dependent Fresnel reflection coefficient at the Si-SiO$_2$ interfaces with normal incidence of light, the Si refractive index ($n_{Si}$) and extinction coefficient ($k_{Si}$), the calculated etalon transmission coefficient exhibits resonances at 764 nm ($\approx n_{Si} \cdot k_{Si}$) and at 560 nm for $t_{Si} = 0.21 \mu m$ (inset of Fig. 4(a)). These agree with the peaks in the EL-spectrum measured within small angles ($\leq 10\degree$) of incidence, including the valley within 650–700 nm. The deviations in the peak and valley locations are likely due to the electronic contribution to $\varepsilon(\lambda)$, not included in the calculation. Note that EL at 560 nm is attributed to processes (transition types A/B in Fig. 4(b)) similar to that in Y-band [24]. For comparison, in 2-terminal AMLEDs excluding FP resonance [32], $\lambda$-peaks were reported near 480 nm, 620 nm, and 700 nm; these were governed only by electronic transitions.

The $\eta_{opt}$ of the AMLET is defined as $P_{opt}/P_{electrical}$, where $P_{electrical} = I_E \cdot V_{EC}$ for $V_{BC} < 0.8$ V and $=I_C \cdot V_{EC}$ for $V_{BC} \geq 0.8$ V. Fig. 5(a) shows that $\eta_{opt}$ increases with increasing $V_{BC}$, and reaches a maximum of $4.3 \times 10^{-5}$ at $V_{BC}=0.8$ V, while $P_{electrical}$ reaches a minimum. A reversal in the direction of $I_B$ demarcates the transition from low to high injection regimes. For $V_{BC} > 0.8$ V, $\eta_{opt}$ reduces due to an eventual increase in $P_{electrical}$. Our AMLET, has a device footprint of 420 $\mu m^2$, emits a total $P_{opt}=43$ nW at $P_{electrical}=10$ mW. Assuming that the light is uniformly emitted from the base region, this translates to an estimated AMLET intensity of 215 mW cm$^{-2}$. The corresponding $P_{opt}$ estimated around the peak $\lambda = 764$ (±19 nm) is 8 nW (intensity $\sim 40$ mW cm$^{-2}$). No significant change in $\varepsilon(\lambda)$ and in $\eta_{opt}$ was observed when the measurements were repeated spanning a continuous operation time of at least $\sim 3$ hours. Comparison of $\eta_{opt}$ versus spectral FWHM with those of prior art is shown in Fig. 5(b). The effects of further narrowing of the base region on $\eta_{opt}$ requires a future study. While a shorter base length would increase the carrier injection, it is also likely to shorten the light-emission region. Further, the impact of varying $t_{Si}$ and temperature on the peak $\lambda$ and $\eta_{opt}$ should be investigated. Based on FP theory, a direct relation between peak $\lambda$ and $t_{Si}$ is expected, while $\eta_{opt}$ will reduce with temperature due to a positive temperature coefficient [37] in $V_{TR}$.

III. CONCLUSION

We presented an avalanche-mode light-emitting transistor in a silicon-on-insulator technology. By combining a high injection current density through a narrow base region with Fabry-Pérot optical resonance in the a thin SOI layer, a high optical power efficiency and a low FWHM was achieved.
