Narrow-band electroluminescence of resonant-cavity avalanche-mode silicon LEDs

S. Dutta,[1] R.J.E. Hueting,[2] and G.J. Verbiest[1]

[1] Delft University of Technology, Dept. of Precision and Microsystems Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands.
[2] University of Twente, Faculty of EEMCS, 7522 NB Enschede, The Netherlands

Monolithic integration of light-emitting diodes (LEDs) in silicon (Si) is gaining attention in various on-chip optoelectronic applications e.g. optical links, micro-displays, and chemical sensing. Operating Si LEDs in avalanche mode leads to electroluminescence (EL) with photon energies exceeding the indirect bandgap of Si, although at low efficiencies. The optical wavelength (λ) of these photons span a wide range of 450 nm - 950 nm, well-matched to the responsivity of Si photodiodes in CMOS technology. A knowledge gap exists on how to enhance the EL intensity within a desired narrow λ-band. Here, we show our recent study on the effect of optical cavity resonances on the phonon-assisted hot-carrier EL in Si LEDs. By employing Fabry-Pérot (FP) resonances in micro-ring diodes in a silicon-on-insulator (iSiPP50G) technology, we show (at room temperature) : (i) the EL peak λ can be tuned across a 100 nm range, (ii) the FWHM of the peak λ can be as low as 50 nm, and (iii) a 1-order-of-magnitude increase in optical power efficiency is achieved. Further, by combining FP resonance with carrier injection in a light-emitting transistor, we report on quasi-monochromatic light-emission near λ ≈760 nm with a record low FWHM of 38 nm.

Introduction

Efficient light-generation in standard silicon (Si) has been a key challenge for monolithic integration of photonic systems in CMOS technology. Despite its low optical power efficiency (η~10^{-6}), electroluminescence (EL) from Si p-n junctions, in particular during avalanche-mode (AM) operation, has gained attention in recent years due to its broad-spectrum ($400 < \lambda < 900$ nm). This spectrum has a significant overlap with the responsivity of Si photodetectors (PDs), which has made the Si AM light-emitting diode (LED) a viable non-coherent light-source in monolithically integrated systems, *e.g.*, optical interconnects, micro-displays and pigment sensors. Nonetheless, it is highly desirable to increase η within a desired (narrow) range of $\Delta\lambda$ for such AMLEDs to boost the performance metrics of the aforesaid systems. In this paper we present our recent findings [1],[2] on η-enhancement and λ-tuneability in AMLEDs and AM light-emitting transistor (LET). Specifically, we show the effect of optical cavity resonances on the phonon-assisted hot carrier EL spectra, that occur during avalanche breakdown of Si p-n junctions.

Experimental devices in iSiPP50G Si photonics technology

<u>Micro-ring LEDs</u>: Each Si micro-ring unit of radius R and width w consists of symmetrically doped half-rings, forming p-n junctions at two opposite ends (Fig. 1a). Highly doped p+ and n+ implants offer ohmic contacts to metal layers routed to bond pads for biasing. For each LED, eleven such ring units are connected in parallel to increase the total device area, and thus light-output. The vertical SOI layer thickness post-fabrication is 0.21 μm. Design variations were included in R (0.6 – 2.0 μm), w (0.16 –

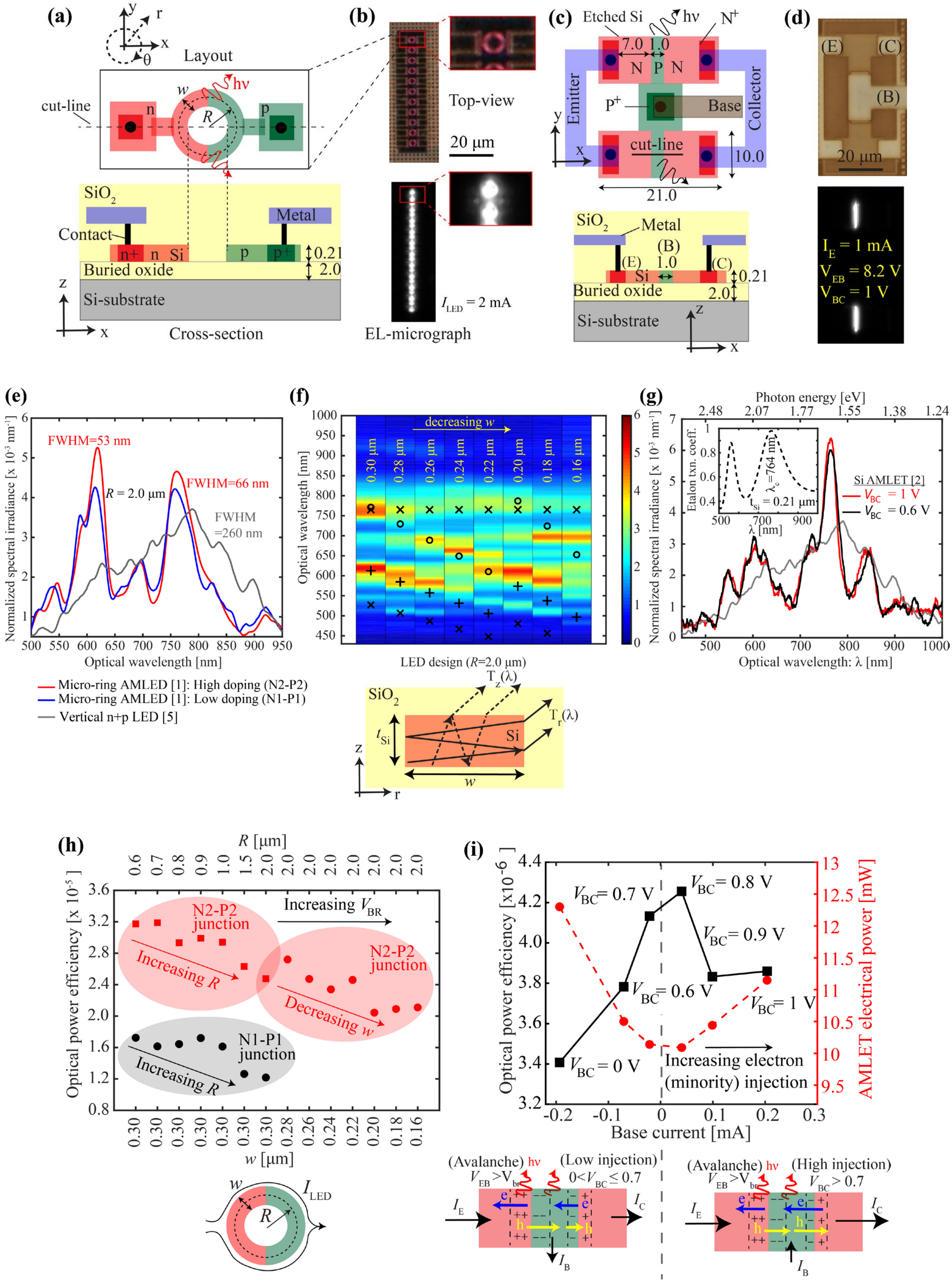
0.30 µm) and doping levels (lightly doped N1/P1 and highly doped N2/P2). The N1/P1 (N2/P2) LEDs show avalanche breakdown voltages (V_{BR}) near ~7 V (~14 V). The micro-rings emit light in AM operation (Fig. 1b).

Avalanche-mode light-emitting transistor (AMLET): The AMLET consists of lateral n-p-n bipolar junctions with symmetrically doped emitter (E), base (B), and collector (C) regions (Fig. 1c,d). The base length is 1.0 µm. The device is placed in a 21 µm x10 µm Si island surrounded by SiO_2 on all faces.

Key results

Micro-ring LEDs: AM-EL from each micro-ring LED was observed as localized bright twin spots from the p-n junctions (Fig. 1b). The EL mechanism is phonon-assisted recombination of hot carriers generated by the electric field at the junction [3],[4]. The intensity of the spots attenuates sharply along the θ-axis of the ring due to the short attenuation length (1-10 µm) of light at short λ in Si, which is close to the round-trip length of the rings. Fig. 1e shows the normalized spectral irradiance $\varepsilon(\lambda)$ of the ring LEDs with R=2.0 µm and w=0.3 µm. Irrespective of the doping level, two dominant narrow spectral bands were observed: $\lambda_{VIS} \approx 620$ nm with FWHM of 53 nm, and $\lambda_{NIR} \approx 764$ nm with FWHM of 66 nm. The relative intensities of these bands are 2-3 times higher than in prior reported Si AMLEDs [5]. Two minor bands near 550 nm and 700 nm were additionally observed. Further, the peak EL wavelengths λ_m of the ring LEDs in the 500 – 700 nm spectral range showed a consistent blue-shift with decreasing w. These results can be explained by FP resonances along the r-axis and z-axis of the Si cavity (Fig. 1f), where the Si-SiO_2 interfaces act as reflective boundaries. The calculated λ_m corresponding to integral resonance modes are in good agreement with the experiment. For a fixed ring geometry, the optical power efficiency ($\eta_{opt} = P_{opt}/P_{LED}$) was higher for the higher (N2/P2) doping level, due to the lower V_{BR} (and so, lower P_{LED}). Further, η_{opt} increased with decreasing R/w ratio (Fig. 1h), which is attributed to a decrease in V_{BR} as the series resistance ($\propto R/w$) is lowered. A maximum η_{opt} of 3.2 x 10^{-5} at P_{LED} = 360 µW per p-n junction, was obtained for R=0.6 µm and w=0.3 µm, a 1-order-of-magnitude improvement compared to that of state-of-the-art Si AMLEDs (Fig. 1j) in various CMOS technologies.

AM light-emitting transistor (AMLET): The AMLET was measured in dc-operation at 298 K in common-base configuration. The E-B junction was set in AM ($V_{EB} > V_{BR}$, I_E = 1 mA) to emit light (Fig. 1d), whereas the B-C junction was forward biased in steps from 0 to 1 V, to inject minority carriers into the base. The AMLET EL spectrum showed three bands (Fig. 1g): Y-band ($\lambda \approx$ 600 nm), R-band ($\lambda \approx$ 764 nm), and NIR band ($\lambda \approx$ 850 nm). The R-band is significantly (2 times) brighter than the other bands. Further, the FWHM of the R-band is only 38 nm, with EL suppression in 650 – 700 nm λ-range, due to to FP-resonance in the 0.21 µm thick SOI layer. As V_{BC} increased from 0 to 0.8 V, η_{opt} increased (Fig. 1i) and reached a maximum at V_{BC}=0.8 V, coinciding with a minimum in $P_{LED}=I_{C(E)}.V_{EC}$, and a reversal in the direction of I_B. For V_{BC} > 0.8 V, η_{opt} decreased due to a subsequent increase in P_{LED}. These are explained as follows. For V_{BC} < 0.8 V, hot electrons (holes) generated in the E-B junction are swept to the E(B) region by the electric field. Only a small fraction of holes are injected into the collector (I_B <0). For V_{BC} > 0.8 V, more holes can transit through the narrow base into the collector, thus I_B > 0. The injected cool electrons from the collector diffuse through the base and initiate avalanche at lower V_{EB}, thereby reducing P_{LED} by transistor action. Recombination of either hot (or cool) electrons with cool (or hot) holes are, thus, the dominant EL-mechanism (favoring the R-band).


(a)
Layout
cut-line
n
p
w
R
hν
SiO2
Contact
Metal
n+ n Si
p p+
0.21
Buried oxide
2.0
Si-substrate
Cross-section
(b)
Top-view
20 µm
I_LED = 2 mA
EL-micrograph
(c)
Etched Si
hν
N+
7.0 1.0
N P N
Emitter
Collector
P+
Base
cut-line
10.0
21.0
SiO2
Metal
(B)
(E) 1.0 (C)
Si
0.21
Buried oxide
2.0
Si-substrate
(d)
(E)
(C)
(B)
20 µm
I_E = 1 mA
V_EB = 8.2 V
V_BC = 1 V
(e)
Normalized spectral irradiance [x 10^-3 nm^-1]
FWHM=53 nm
R = 2.0 µm
FWHM=66 nm
FWHM =260 nm
Optical wavelength [nm]
Micro-ring AMLED [1]: High doping (N2-P2)
Micro-ring AMLED [1]: Low doping (N1-P1)
Vertical n+p LED [5]
(f)
decreasing w
0.30 µm
0.28 µm
0.26 µm
0.24 µm
0.22 µm
0.20 µm
0.18 µm
0.16 µm
Optical wavelength [nm]
LED design (R=2.0 µm)
SiO2
T_z(λ)
T_r(λ)
t_Si
Si
w
(g)
Photon energy [eV]
Normalized spectral irradiance [x 10^-3 nm^-1]
Etalon txn. coeff.
λ_c=764 nm
t_Si = 0.21 µm
λ [nm]
Si AMLET [2]
V_BC = 1 V
V_BC = 0.6 V
Optical wavelength: λ [nm]
(h)
R [µm]
Optical power efficiency [x 10^-5]
N2-P2 junction
Increasing R
Increasing V_BR
N2-P2 junction
Decreasing w
N1-P1 junction
Increasing R
w [µm]
w
I_LED
R
(i)
Optical power efficiency [x10^-6]
AMLET electrical power [mW]
V_BC= 0.7 V
V_BC= 0.8 V
V_BC= 0.9 V
V_BC= 0.6 V
V_BC= 1 V
V_BC= 0 V
Increasing electron (minority) injection
Base current [mA]
(Avalanche) hν V_EB>V_br
(Low injection) 0<V_BC≤0.7
(Avalanche) hν V_EB>V_br
(High injection) V_BC> 0.7
I_E
I_C
I_B
e
h

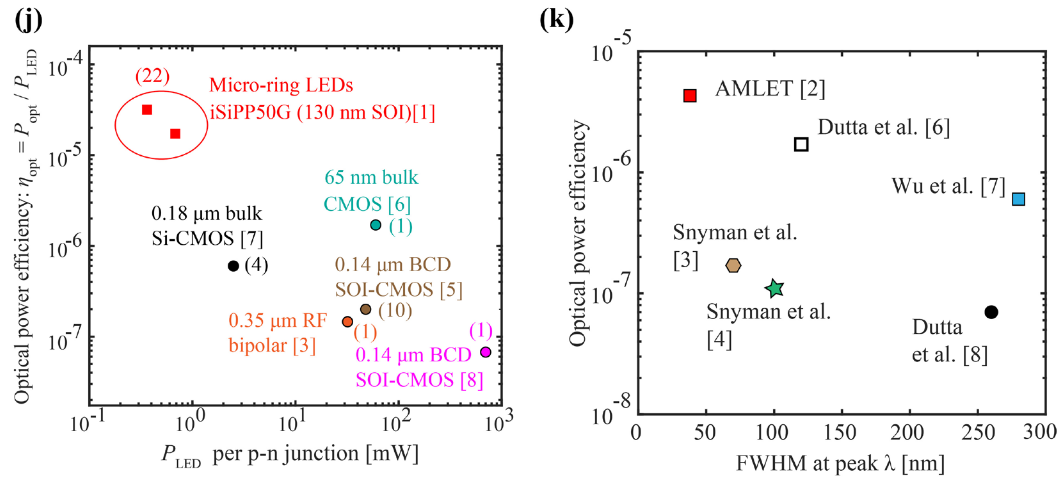


Figure 1: (a) Schematic layout along with the device cross-section of a micro-ring LED unit [1]. Indicated dimensions are in µm. Doping levels n/p, ring width *w* and radius *R* were varied in the LED designs. **(b)** Top-view of a micro-ring LED and its AM-EL micrograph captured at the indicated electrical bias. **(c)** Schematic layout and device cross-section of the AMLET [2] realized with a n-p-n bipolar junction. **(d)** AMLET top-view and its AM-EL micrograph at the indicated electrical bias. All devices were fabricated in the iSiPP50G Si photonics technology. The EL micrographs were captured with a 20 s integration time. **(e)** Normalized $\varepsilon(\lambda)$ of ring LEDs with identical geometry (R=2 µm, w=0.3 µm), but with different doping levels. The $\varepsilon(\lambda)$ of a prior-reported n^+p AMLED [5] is shown in grey for comparison. **(f)** $\varepsilon(\lambda)$ versus w for N2/P2 doped ring LEDs. The symbols **o,+,x** denote the calculated Fabry-Pérot (FP) resonance peak wavelengths corresponding to each w and to the 0.21 µm thickness of Si layer. **(g)** Normalized $\varepsilon(\lambda)$ of the AMLET at the indicated biasing, showing peak emission at 764 nm. **(h)** η_{opt} versus R and w for the micro-ring LEDs. **(i)** AMLET η_{opt} (black) and P_{LED} (red) at I_E =1 mA and varying I_B. The schematic at the bottom shows the AMLET operation under low and high injection. **(j)** Benchmark of η_{opt} versus PLED per p-n junction against prior art for Si AMLEDs [3],[5]-[8]. **(k)** Benchmark for η_{opt} versus FWHM at peak λ of the AMLET against those for prior art Si AM LED(T)s [3],[4],[6]-[8].

Conclusion

We reported on narrow band electroluminescence (EL) of avalanche-mode (AM) silicon (Si) p-n junction devices, by employing Fabry-Pérot (FP) resonances and carrier injection. Micro-ring cavity LEDs were studied to optically confine the light along two dimensions, leading to narrow-band EL peaks within the visible (500-700 nm) and near-infrared spectra (750-800 nm), with a 2-3 fold higher intensity and a 10-fold higher optical power efficiency compared to state-of-the-art AM Si LEDs. The peak EL-wavelengths depend on the ring width, as predicted by a FP resonator model. Further, we realized an AM Si light-emitting transistor. A high injection current density through a narrow base region combined with FP resonance in the optically thin SOI layer, resulting in near quasi-monochromatic light-emission centered at 764 nm with a record low bandwidth of 38 nm.

References

[1] S. Dutta and G.J. Verbiest, Optics Express, vol. 30, no. 23 (in press), 2022.
[2] S. Dutta, R.J.E. Hueting, and G.J. Verbiest, IEEE Electron Device Lett., vol. 43, no. 10, pp. 1701-1704, 2022.
[3] L.W. Snyman et al., IEEE J. Quantum Electron., vol. 53, no. 5, p. 7100209, 2017.
[4] L.W. Snyman, K. Xu, and J.-L. Polleux, IEEE J. Quantum Electron., vol. 56, no. 4, p. 3200210, 2020.
[5] S. Dutta et al., IEEE Trans. Electron Devices, vol. 64, no. 4, pp. 1612-1618, 2017.
[6] S. Dutta et al., IEEE Electron Device Lett., vol. 38, no. 7, pp. 898-901, 2017.
[7] K. Wu et al., IEEE Electron Device Lett., vol. 42, no. 4, pp. 541-544, 2021.
[8] S. Dutta et al., Optics Express, vol. 25, no. 5, pp. 5440-5456, 2017.