Electrical TCAD Study of the Low-Voltage Avalanche-Mode Superjunction LED

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Abstract—The CMOS silicon avalanche-mode light-emitting diode (AMLED) has emerged as a potential light source for monolithic optical interconnects. Earlier we presented a superjunction light-emitting diode (SJLED) that offers a higher electroluminescent intensity compared to a conventional AMLED because of its more uniform field distribution. However, for reducing power consumption low-voltage ($\leq 15V$) SJLEDs are desired, not explored before. In this work we present a TCAD simulation feasibility study of the low-voltage SJLED for various doping concentrations and device dimensions. The results show that for obtaining a constant field, approximately a tenfold more aggressive charge balance condition in the SJLED is estimated than traditionally reported. This is important for establishing a guideline to realize optimized RESURF and SJLEDs in the ever-shrinking advanced CMOS nodes.

Index Terms—Avalanche breakdown, Diode, Light-Emitting Diode (LED), Power, silicon

I. INTRODUCTION

In the 1950's it was discovered that silicon (Si) pn-junctions operating in avalanche breakdown exhibit broad-spectrum electro-luminescence (EL) at short wave lengths ($\lambda \sim 350\text{-}900\text{nm}$), although with a low internal quantum efficiency ($\eta_{\text{RAD}} \sim 10^{-5}$) [1], [2]. After this discovery it took practically half a century for research on Si avalanche-mode light emitting diodes (AMLEDs) to gain momentum ([3]–[9]). This can be partly attributed to the advancement of commercial CMOS technology driven by the strong demand for more on-chip functionality. In addition, Si AMLEDs exhibit significant spectral overlap with the responsivity of Si photodiodes [10] which is beneficial for on-chip optical interconnects.

Due to a wide variety of commercial CMOS technologies, various approaches have been reported to increase η_{RAD} of AMLEDs:

- Additional carrier injection via a third terminal in AMLEDs [11].
- Carrier energy and momentum engineering [12], [13].
- The superjunction light-emitting diode (SJLED) [14], [15].

In this work we focus on the last approach. The basic idea of the SJLED is to mimic a p-i-n diode, see Fig. 1(a), at avalanche breakdown. The constant electric field distribution

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Fig. 1. Schematic top view of the (a) p-i-n diode and (b) SJLED. In theory the p/n poles are infinitely repeated in the y-direction. Line A-A' indicates the axis of symmetry of the device. The drift length of both devices and pole width are indicated by L respectively d . The anode/cathode regions have a doping of 10^{19} cm^{-3} . (c) Breakdown field distributions of a 5V and 15V p-i-n diode compared to their effective field obtained from a 1D nonlocal avalanche model (dotted curves) using Eqs. (3)–(4). (d) Breakdown voltage (BV) against L of the Si p-i-n diode obtained from TCAD simulations [23] and measurements (open red symbols) [27]. The grey dashed line represents results obtained from Fulop's approximation [30], showing a discrepancy for smaller L .

at breakdown ($\mathcal{E}_x(x)$) in the drift (or "active") region of the p-i-n diode, see Fig. 1(c), results in a higher EL-intensity thus η_{RAD} compared to conventional pn junctions with the same breakdown voltage (BV) [14]. In the latter $\mathcal{E}_x(x)$ is triangularly shaped and hence only near the peak field, light emission spots will form.

However, to realize a p-i-n diode in standard CMOS technology is difficult. Therefore, the widely adopted reduced surface field (RESURF) effect [16], [17], [18] in power devices is used by placing multiple parallel p/n-layers or "poles", *i.e.* superjunction RESURF, see Fig. 1(b). In this way the p/n poles can be fully depleted at avalanche breakdown akin to the intrinsic region of a p-i-n diode.

For obtaining the optimal RESURF condition, thus a constant $\mathcal{E}_x(x)$, the product of pole width (d) and pole doping concentration (N) must satisfy the charge balance condition [19], [17], [16]:

$$N \cdot d \lesssim |\mathcal{E}_{c,y}| \frac{2\varepsilon_s}{q}, \quad (1)$$

where $\mathcal{E}_{c,y}$ is the critical (or breakdown) field of the one dimensional (1D) vertical (y-direction) p/n poles, ε_s is the permittivity, and q is the elementary charge. Typically, the charge balance condition in Si is reported to be $N \cdot d \lesssim 10^{12}$

cm^{-2} [16], but this value increases for higher N ($\approx 10^{18} \text{ cm}^{-3}$) since the ionization rate strongly depends on the field; this increases $\mathcal{E}_{c,y}$ of the 1D p/n poles [20]. Moreover because of mobility reduction $\mathcal{E}_{c,y}$ increases with N as well. Provided that Eq. (1) holds, the BV of the SJLED is determined by $\mathcal{E}_{c,x}$, as in the p-i-n diode.

At breakdown the constant field in the p-i-n diode (and optimized SJLED) reaches the critical field ($\mathcal{E}_x(x) = \mathcal{E}_{c,x}$) uniformly. Consequently, as shown in Fig. 1(d) $BV \approx |\mathcal{E}_{c,x}| \cdot L$, where L is the drift length. Importantly, for low-voltage (LV) devices $\mathcal{E}_{c,x}$ strongly increases for smaller L , see also Fig. 1(c). It can be derived that

$$|\mathcal{E}_{c,x}| = \frac{b_n}{\ln(a_n L)}, \quad (2)$$

where $a_n = 7.03 \cdot 10^5 \text{ cm}^{-1}$ and $b_n = 1.23 \cdot 10^6 \text{ V/cm}$ for Si.

Particularly for reducing power consumption, LV SJLEDs are desired but for $BV < 5\text{V}$ nonlocal avalanche (NLA) effects will dramatically drop the EL-intensity [21], obviously not desired. In addition, band-to-band tunneling (BTBT) effects [22] will then play a role. So far SJLEDs have been studied for $BV \gtrsim 25\text{V}$. In this work we report a TCAD simulation study to investigate the impact of the $N \cdot d$ value on the uniformity of $\mathcal{E}_x(x)$ and BTBT effects in LV SJLEDs ($BV \leq 15\text{V}$), both important for increasing η_{RAD} , aiming at (relatively) LV light generation.

II. RESULTS AND DISCUSSION

Earlier, we reported TCAD and experimental data of SJLEDs for $25\text{V} \leq BV \leq 50\text{V}$ [14]. Best results were obtained for $N \approx 2 \cdot 10^{17} \text{ cm}^{-3}$ and a minimum $d \approx 0.38 \mu\text{m}$, both defined by technology constraints. The SJLEDs ($L = 2 \mu\text{m}$) showed about a 1.7 fold increase in breakdown voltage ($BV = 50\text{V}$) compared to that of conventional (pn-junction) AMLEDs ($BV = 29\text{V}$) of the same size and realized in the same technology. Also, the EL intensity that was measured for the same current from 400 nm to 870 nm (with a peak at 650 nm) wavelength, was almost 2 times higher than that of conventional counterparts as confirmed by the two times higher measured coupling efficiency ($\sim 8 \cdot 10^{-9}$) for the former. Those reported results therefore show that the SJLED has a more uniform field distribution. However for that SJLED, $N \cdot d \approx 7.7 \cdot 10^{12} \text{ cm}^{-2}$ which is higher than the charge balance condition [16], implying that so far we did not obtain optimal RESURF.

Fig. 2 shows $\mathcal{E}_x(x) = \mathcal{E}_{c,x}$ of the 15 V p-i-n diode ($L = 350\text{nm}$) obtained from TCAD simulations [23]. Throughout this work we have used Selberherr's local impact ionization model [24] that considers for fields higher than $4 \cdot 10^5 \text{ V/cm}$ (applicable in this work) impact ionization coefficients according to $\alpha_{n(p)} = a_{n(p)} \cdot \exp\left(-\left(\frac{b_{n(p)}}{\mathcal{E}}\right)^{\beta_{n(p)}}\right)$, where $a_p = 6.71 \cdot 10^5 \text{ cm}^{-1}$, $b_p = 1.69 \cdot 10^6 \text{ V/cm}$, and $\beta_{n(p)} = 1$. For comparison, $\mathcal{E}_x(x)$ is shown of the SJLED with $N \cdot d \approx 7.7 \cdot 10^{12} \text{ cm}^{-2}$ [14], taken from the line A-A', see Fig. 1(b). As expected, in the SJLED $\mathcal{E}_x(x)$ is not constant: at the left junction there is a peak field. This will result in more light emission near this junction (this could not be observed in our

Fig. 2. Breakdown field distribution of the 15V p-i-n diode and 15V SJLED obtained from TCAD simulations (both $L = 350\text{nm}$), using reported values for $N \approx 2 \cdot 10^{17} \text{ cm}^{-3}$ and $d \approx 0.38 \mu\text{m}$ [14]. For the SJLED $\mathcal{E}_x(x)$ is taken from line A-A' (Fig. 1(b)), and through the junction of a p/n pole as indicated by, e.g., line B-B' (Fig. 1(b)).

experiments [14] possibly due to the limited image resolution) rather than throughout the whole drift region as would be the case for the p-i-n diode. Clearly, for increasing the EL intensity the latter is desired.

Fig. 3. 2D potential contour plots at breakdown in unit cells of (a) the SJLED for $N \approx 2 \cdot 10^{17} \text{ cm}^{-3}$, $d \approx 0.38 \mu\text{m}$, $L = 350\text{nm}$ (see also Fig. 2), (b) and (c) the optimized SJLED for $N = 10^{18} \text{ cm}^{-3}$ and $d = 10\text{nm}$ and $L = 350\text{nm}$, respectively, 32nm . (d) Example of a 2D meshing plot used for obtaining figure (b) showing a dense mesh in the drift region (350 mesh points in x -direction and 30 mesh points in y -direction).

We have performed extensive TCAD simulations to optimize the SJLED for $BV = 5\text{V}$ and 15V by incorporating three doping concentrations: $N = 10^{16}$, $2 \cdot 10^{17}$, and 10^{18} cm^{-3} .

Fig. 3(a) depicts a 2D potential contour plot at breakdown in a unit cell of the SJLED with previously mentioned values of N and d [14], showing that the potential lines are not equidistant and strongly curved. For comparison contour plots are shown of optimized counterparts for $N = 10^{18} \text{ cm}^{-3}$, $d = 10\text{nm}$ and $L = 350\text{nm}$ (Fig 3(b)), respectively, 32nm (Fig 3(c)) both indicating optimal RESURF. For the p-i-n diode the same results are obtained where we have used about 1,200 (4,000) mesh points for $L = 32\text{nm}$ (350nm), in which the drift region has 32 (350) mesh points in x -direction and 10 mesh points in y -direction. For the optimization of the SJLED we have used about 1,200-22,000 mesh points depending the doping and size. Here, in the drift region we have used for $L = 32\text{nm}$ (350nm) 32 (350) mesh points in x -direction and 30-40 mesh points in y -direction, see for example Fig. 3(d).

The optimization routine we have used is as follows. First L needs to be determined for the 5V and 15V p-i-n diodes,

Fig. 4. Lateral breakdown field distribution obtained from TCAD simulations of 15V (left) and 5V SJLEDs for $N = 10^{18} \text{ cm}^{-3}$ (top), $2 \cdot 10^{17} \text{ cm}^{-3}$ (middle) and 10^{16} cm^{-3} (bottom). In all cases d is varied for obtaining a constant field for $d=100 \text{ nm}$ ($N = 10^{16} \text{ cm}^{-3}$, 15V) and $d=10 \text{ nm}$ ($N = 2 \cdot 10^{17}$ and 10^{18} cm^{-3}). One exception: for 5V and $N = 10^{16} \text{ cm}^{-3}$ $N \cdot d$ has hardly any effect.

see Fig. 1(d). These lengths, 32nm resp. 350nm long, are then used for the 5V respectively 15V SJLEDs. Next, for each L d is varied for all N such that a (practically) constant $\mathcal{E}_x(x)$ is obtained. Fig. 4 summarizes $\mathcal{E}_x(x)$ for all SJLEDs. Using Eq. (1) from this part of the study it can be concluded that $N \cdot d \lesssim 10^{11} \text{ cm}^{-2}$ for $N = 10^{16}$ and $2 \cdot 10^{17} \text{ cm}^{-3}$, while $N \cdot d \lesssim 10^{12} \text{ cm}^{-2}$ for $N = 10^{18} \text{ cm}^{-3}$. For the latter $N \cdot d$ is estimated higher because of the higher $\mathcal{E}_{c,y}$ ($\sim 1.2 \text{ MV/cm}$ [20]). Furthermore, for 5V $N = 10^{16}$ $\mathcal{E}_x(x)$ is hardly affected by d and is less uniform than for higher N . This can be attributed to the very high $\mathcal{E}_{c,x}$ ($\sim 1.48 \text{ MV/cm}$) compared to $\mathcal{E}_{c,y}$ ($\sim 0.3 \text{ MV/cm}$). In summary, for low N superjunction RESURF is not needed, but for all other cases for obtaining a constant breakdown field a tenfold lower charge balance in LV SJLEDs is required, which was not reported earlier [16].

Fig. 5. Reverse IV characteristics of the optimized 5 V and 15 V SJLEDs ($d=10 \text{ nm}$ for 10^{18} cm^{-3}) compared to those of 5 V and 15 V p-i-n diodes (dotted lines). Inset: forward characteristics of the devices.

Further, we study the IV characteristics of the optimized SJLEDs for $N = 10^{18} \text{ cm}^{-3}$, see Fig. 5, where default models and parameter values for concentration dependent Shockley-Read Hall (SRH) [25] and Auger recombination, the charge carrier mobility [26] and BTBT [22] are used. The 15V devices show lower leakage currents than the 5V counterparts due to BTBT. Interestingly, despite the high N in the 5V SJLED, BTBT has not increased compared to the 5V p-i-n diode due to the RESURF effect. The differences between the characteristics of the 15V SJLED and p-i-n diode at low forward and reverse bias is caused by recombination: the higher doping in the SJLED reduces the (effective) lifetime [25] that in turn increases the leakage and low forward current. In addition, the increased doping in the drift region causes a lower series resistance in the SJLED yielding a higher maximum current density than for the p-i-n diode.

Finally, for $BV \lesssim 5 \text{ V}$ NLA effects will become important in 1D p^+-n diodes [21]. NLA effects can play a role in 1D p-i-n diodes [27], and consequently SJLEDs [28], as well.

It can be derived for the effective field formed by NLA that [29]

$$\mathcal{E}_{\text{NLA}}(x, y) = \frac{5}{2} \cdot \frac{k \Delta T_e(x, y)}{q \lambda_e}, \quad (3)$$

where ΔT_e is the increase in electron temperature and λ_e is the mean free path of electrons ($\sim 65 \text{ nm}$ in Si). For both the p-i-n diode and SJLED holds [28]

$$\Delta T_e(x) = \frac{2q\mathcal{E}_x(x)\lambda_e}{5k} \cdot \left[1 - \exp\left(-\frac{x}{\lambda_e}\right) \right]. \quad (4)$$

For the SJLED an effective vertical field ($\mathcal{E}_{\text{NLA}}(y)$) can be obtained similar to that of a single sided junction [29]. Typically, the obtained $\mathcal{E}_{\text{NLA}}(x, y)$ is less than the (local) $\mathcal{E}(x, y)$. For determining the breakdown field Eqs. (3)-(4) should be substituted in the ionization integral that is equated to unity. This basically implies that BV increases for the same device dimensions once NLA becomes important [27].

By adopting Eqs. (3)-(4), Fig. 1(c) shows that particularly for the 5V p-i-n diode $\mathcal{E}_{\text{NLA},x}(x) < \mathcal{E}_x(x)$ ($\mathcal{E}_{\text{NLA},x}(x)$ is indicated by the dotted curve), hence NLA is then important. However, it is expected that even in the 15V SJLED, NLA will play a role because of the relatively high vertical (y -direction) field ($\sim 1.2 \text{ MV/cm}$) at nm-scale dimension, even a higher field than for the 5V 1D p^+-n diode. Because $\mathcal{E}_{\text{NLA},c,y}$ will then be higher than $\mathcal{E}_{c,y}$, NLA relaxes the charge balance condition (see Eq. (2)). As a result, especially for $d = 10 \text{ nm}$ $N \cdot d$ can then become higher than reported in this work. This requires both a thorough experimental and theoretical future study.

III. CONCLUSIONS

An extensive TCAD simulation study has been performed to optimize low-voltage superjunction light-emitting diodes (SJLEDs). The results show that a tenfold more aggressive charge balance condition is required than traditionally reported for power devices. Also, because of the reduced peak field, band-to-band tunneling is less important for SJLEDs than for their conventional counterparts. This work will serve as a guideline for device design in future scaled CMOS nodes.

REFERENCES

- [1] R. Newman, "Visible light from a silicon p-n junction", *Phys. Rev.*, vol. 100, no. 2, pp. 700-703, 1955.
- [2] A.G. Chynoweth and K.G. McKay, "Photon emission from avalanche breakdown in silicon", *Phys. Rev.*, vol. 102, no. 2, pp. 369-376, 1956.
- [3] M. D. Plessis, H. Aharoni, and L. W. Snyman, "Silicon LEDs fabricated in standard VLSI technology as components for all silicon monolithic integrated optoelectronic systems", *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 6, pp. 1412-1419, 2002.
- [4] B. Huang, X. Zhang, W. Wang, Z. Dong, N. Guan, Z. Zhang, and H. Chen, "CMOS monolithic optoelectronic integrated circuit for on-chip optical interconnection", *Optics Communications*, vol. 284, no. 16-17, pp. 3924-3927, 2011.
- [5] A. Khanmohammadi, R. Enne, M. Hofbauer, and H. Zimmermann, "Monolithically integrated optical random pulse generator in high voltage CMOS technology", *Proc. 45th ESSDERC*, pp. 138-141, 2015.
- [6] V. Agarwal, S. Dutta, A. J. Annema, R. J. E. Hueting, J. Schmitz, M.-J. Lee, E. Charbon and B. Nauta, "Optocoupling in CMOS", *International Electron Device Meeting (IEDM)*, *Techn. Digest*, pp. 739-742, 2018.
- [7] K. Xu, "Silicon MOS Optoelectronic Micro-Nano Structure Based on Reverse-Biased PN Junction", *Phys. Stat. Sol.*, vol. 216, no. 7, p. 1800868, 2019.
- [8] S.K. Lazarouk, A.A. Leshok, T.A. Kozlova, A.V. Dolblik, L.D. Vi, V.K. Ilkov, and V.A. Labunov, "3D Silicon Photonic Structures Based on Avalanche LED with Interconnections through Optical Interposer", *Int. J. Nanoscience*, vol. 18, no. 03n04, p. 1940091, 2019.
- [9] M. Krakkers, T. Knezevic, K.M. Batenburg, X. Liu, and L.K. Nanver, "Diode design for studying material defect distributions with avalanche-mode light emission", *IEEE Int. Conf. Microelectronic Test Structures (ICMTS)*, 2020.
- [10] B.P. van Drieënhuizen and R.F. Wolffenbuttel, "Optocoupler based on the avalanche light emission in silicon", *Sens. Actuators A: Phys.*, vol. 31, pp. 229-240, 1992.
- [11] L.W. Snyman, M. du Plessis, and H. Aharoni, "Injection-avalanche based n^+pn silicon complementary metal-oxide-semiconductor light-emitting device (450–750 nm) with 2-order-of-magnitude increase in light emission intensity", *Jpn. J. Appl. Phys.*, vol. 46, no. 4B, pp. 2474-2480, 2007.
- [12] L.W. Snyman, K. Xu, J.-L. Polleux, K.A. Ogudo, and C. Viana, "Higher Intensity SiAvLEDs in an RF Bipolar Process Through Carrier Energy and Carrier Momentum Engineering", *IEEE J. Quantum Electr.*, vol. 51, no. 7, p. 3200110, 2015.
- [13] L.W. Snyman, K. Xu, and J. Polleux, "Micron and Nano-Dimensioned Silicon LEDs Emitting at 650 and 750-850 nm Wavelengths in Standard Si Integrated Circuitry", *IEEE J. Quantum Electr.*, vol. 56, no. 4, p. 3200210, 2020.
- [14] S. Dutta, P.G. Steeneken, V. Agarwal, J. Schmitz, A.J. Annema, and R.J.E. Hueting, "The Avalanche-Mode Superjunction LED", *IEEE Trans. Electr. Dev.*, vol. 64, no. 4, pp. 1612-1618, 2017.
- [15] R.J.E. Hueting, S. Dutta, V. Agarwal, and A.J. Annema, "Figures of merit of avalanche-mode silicon LEDs", *Proc. SPIE, Fifth Conference on Sensors, MEM, and Electro-Optic Systems*, p. 1104305, 2019.
- [16] J.A. Appels and H.M.J. Vaes, "High voltage thin layer devices (RESURF devices)", *International Electron Device Meeting (IEDM)*, *Techn. Digest*, pp. 238-241, 1979.
- [17] A. Ferrara, B.K. Boksteen, R.J.E. Hueting, A. Heringa, J. Schmitz, and P.G. Steeneken "Ideal RESURF Geometries", *IEEE Trans. Electr. Dev.*, vol. 62, no. 10, pp. 3341-3347, 2015.
- [18] F. Udrea, G. Deboy, and T. Fujihira, "Superjunction power devices, history, development, and future prospects", *IEEE Trans. Electr. Dev.*, vol. 64, no. 3, pp. 713-727, 2017.
- [19] T. Fujihira, "Theory of semiconductor superjunction devices", *Jpn. J. Appl. Phys.*, vol. 36, no. 10, pp. 6254-6262, 1997.
- [20] S.M. Sze and K.K. Ng, "Physics of Semiconductor Devices", *Hoboken, NJ, USA, Wiley*, 3rd edition, 2007.
- [21] S. Dutta, R.J.E. Hueting, A.J. Annema, L. Qi, L.K. Nanver, and J. Schmitz, "Opto-electronic modeling of light emission from avalanche-mode silicon p+n junctions", *J. Appl. Phys.*, vol. 118, p. 114506, 2015.
- [22] G.A.M. Hurkx, D.B.M. Klaassen, and M.P.G. Knuvers, "A new recombination model for device simulation including tunneling", *IEEE Trans. Electr. Dev.*, vol. 39, no. 2, pp. 331-338, 1992.
- [23] *Atlas device simulation software*, v. 5.30.0.R, *Silvaco, Inc., Santa Clara, CA, USA*, 2020
- [24] S. Selberherr, *Analysis and Simulation of Semiconductor Devices*, Springer-Verlag, New-York, 1984.
- [25] D.J. Roulston, N.D. Arora, and S.G. Chamberlain, "Modeling and Measurement of Minority-Carrier Lifetime versus Doping in Diffused Layers of n^+p Silicon Diodes", *IEEE Trans. Electron Devices*, Vol. 29, pp. 284-291, 1982.
- [26] D.B.M. Klaassen, "A Unified Mobility Model for Device Simulation-I. Model Equations and Concentration Dependence", *Solid-State Electronics*, vol. 35, no. 7, pp. 953-959, 1992.
- [27] P. Agarwal, M. J. Goossens, V. Zieren, E. Aksen, and J. W. Slotboom, "Impact ionization in thin silicon diodes", *IEEE Electr. Dev. Lett.*, vol. 25, no. 12, pp. 807-809, 2004.
- [28] S. Dutta, "Avalanche-mode Silicon LEDs for monolithic optical coupling in CMOS technology", *PhD thesis*, Enschede, November 2017.
- [29] J.W. Slotboom, G. Streutker, M.J. van Dort, P.H. Woerlee, A. Pruijboom, and D.J. Gravesteijn, "Non-local impact ionization in silicon devices", *International Electron Device Meeting (IEDM)*, *Techn. Digest*, pp. 127-130, 1991.
- [30] W. Fulop, "Calculation of avalanche breakdown voltages of silicon p-n junctions", *Solid-State Electr.*, vol. 10, pp. 39-43, 1967.