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

R.J.E. Hueting, *Senior Member, IEEE*, H. de Vries, S. Dutta, and A.J. Annema, *Member, IEEE*

**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

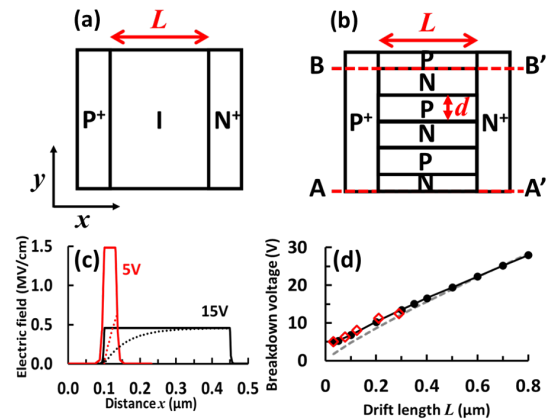
In the 1950's it was discovered that silicon (Si) p-n junctions operating in avalanche breakdown exhibit broad-spectrum electro-luminescence (EL) at short wave lengths ( $\lambda \sim 350-900\text{nm}$ ), although with a low internal quantum efficiency ( $\eta_{\text{RAD}} \sim 10^{-5}$ ) [1], [2]. After 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  $\eta_{\text{RAD}}$  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  $10^{19} \text{ cm}^{-3}$ . (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  $\eta_{\text{RAD}}$  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]:

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

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

$\text{cm}^{-2}$  [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  $BV < 5V$  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  $BV \approx 25V$ . 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 ( $BV \leq 15V$ ), both important for increasing  $\eta_{\text{RAD}}$ , aiming at (relatively) LV light generation.

## II. RESULTS AND DISCUSSION

Earlier, we reported TCAD and experimental data of SJLEDs for  $25V \leq BV \leq 50V$  [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 ( $BV = 50V$ ) compared to that of conventional (pn-junction) AMLEDs ( $BV = 29V$ ) 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

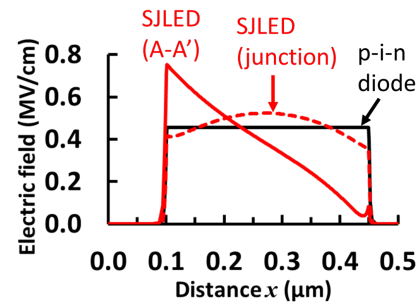


Fig. 2. Breakdown field distribution of the 15V p-i-n diode and 15V SJLED obtained from TCAD simulations (both  $L = 350\text{nm}$ ), using reported values for  $N \approx 2 \cdot 10^{17} \text{ cm}^{-3}$  and  $d \approx 0.38 \mu\text{m}$  [14]. For the SJLED  $\mathcal{E}_x(x)$  is taken from line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

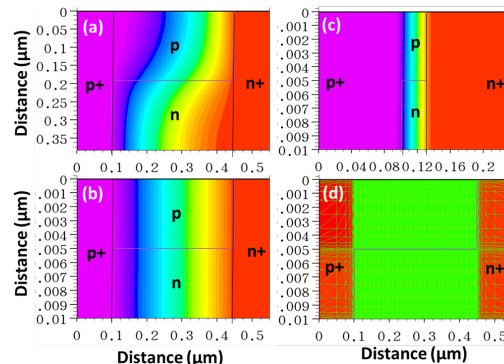


Fig. 3. 2D potential contour plots at breakdown in unit cells of (a) the SJLED for  $N \approx 2 \cdot 10^{17} \text{ cm}^{-3}$ ,  $d \approx 0.38 \mu\text{m}$ ,  $L = 350\text{nm}$  (see also Fig. 2), (b) and (c) the optimized SJLED for  $N = 10^{18} \text{ cm}^{-3}$  and  $d = 10\text{nm}$  and  $L = 350\text{nm}$ , respectively,  $32\text{nm}$ . (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  $BV = 5V$  and  $15V$  by incorporating three doping concentrations:  $N = 10^{16}$ ,  $2 \cdot 10^{17}$ , and  $10^{18} \text{ cm}^{-3}$ .

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,  $32\text{nm}$  (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  $L = 32\text{nm}$  ( $350\text{nm}$ ), 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  $L = 32\text{nm}$  ( $350\text{nm}$ ) 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,

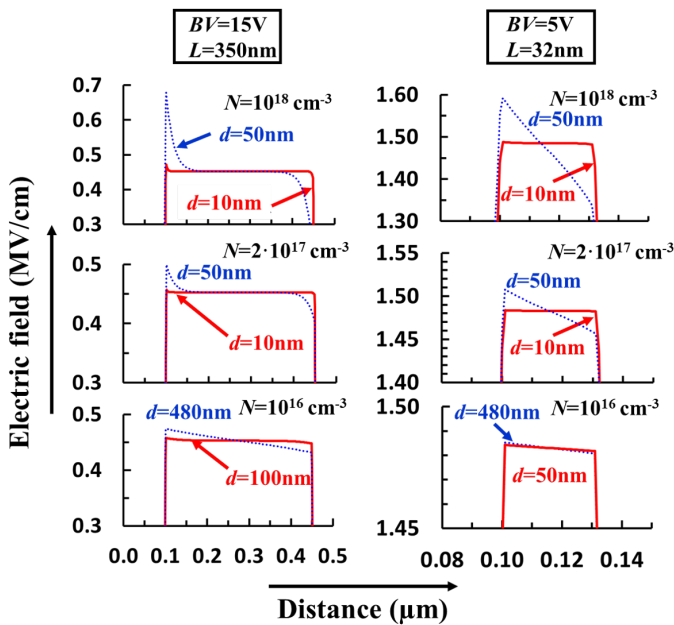


Fig. 4. Lateral breakdown field distribution obtained from TCAD simulations of 15V (left) and 5V SJLEDs for  $N = 10^{18} \text{ cm}^{-3}$  (top),  $2 \cdot 10^{17} \text{ cm}^{-3}$  (middle) and  $10^{16} \text{ cm}^{-3}$  (bottom). In all cases  $d$  is varied for obtaining a constant field for  $d=100 \text{ nm}$  ( $N = 10^{16} \text{ cm}^{-3}$ , 15V) and  $d=10 \text{ nm}$  ( $N = 2 \cdot 10^{17}$  and  $10^{18} \text{ cm}^{-3}$ ). 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  $N \cdot d \gg 10^{11} \text{ cm}^{-2}$  for  $N = 10^{16}$  and  $2 \cdot 10^{17} \text{ cm}^{-3}$ , while  $N \cdot d \gg 10^{12} \text{ cm}^{-2}$  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].

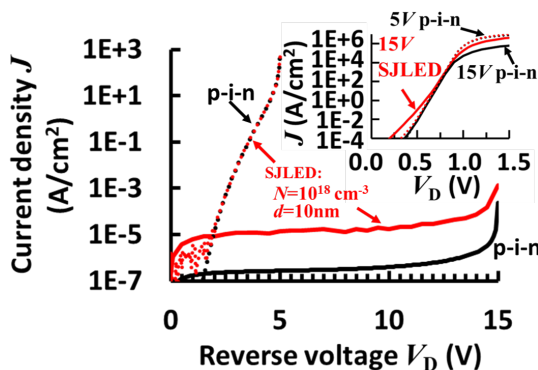


Fig. 5. Reverse  $IV$  characteristics of the optimized 5 V and 15 V SJLEDs ( $d=10 \text{ nm}$  for  $10^{18} \text{ cm}^{-3}$ ) compared to those of 5 V and 15 V p-i-n diodes (dotted lines). Inset: forward characteristics of the devices.

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<sup>+</sup>-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  $\Delta T_e$  is the increase in electron temperature and  $\lambda_e$  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<sup>+</sup>-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.

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