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 (<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 ($\lambda \sim 350$-900nm), 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 responsitivity 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 avalanche breakdown. The constant electric field distribution

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 p-n 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]:

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

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 $N \cdot d \lesssim 10^{12}$

![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 symbol) [27]. The grey dashed line represents results obtained from Fulop’s approximation [30], showing a discrepancy for smaller $L$.](image-url)
cm$^{-2}$ [16], but this value increases for higher $N$ ($\gtrsim 10^{18}$ cm$^{-3}$) since the ionization rate strongly depends on the field; this increases $\xi_{c,y}$ of the 1D p/n poles [20]. Moreover because of mobility reduction $\xi_{c,y}$ increases with $N$ as well. Provided that Eq. (1) holds, the $BV$ of the SJLED is determined by $\xi_{c,x}$, 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 ($\xi_{c,x}(x) = \xi_{c,x}$) uniformly. Consequently, as shown in Fig. 1(d) $BV \approx |\xi_{c,x}| \cdot L$, where $L$ is the drift length. Importantly, for low-voltage (LV) devices $\xi_{c,x}$ strongly increases for smaller $L$, see also Fig. 1(c). It can be derived that

$$|\xi_{c,x}| = \frac{b_n}{\ln(a_nL)},$$

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

Particularly for reducing power consumption, LV SJLEDs are desired but for $BV < 5$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 $BV \gtrsim 25$V. In this work we report a TCAD simulation study to investigate the impact of the $N \cdot d$ value on the uniformity of $\xi_{c,x}$ and BTBT effects in LV SJLEDs ($BV \leq 15$V), both important for increasing $\eta_{RAD}$, aiming at (relatively) LV light generation.

II. RESULTS AND DISCUSSION

Earlier, we reported TCAD and experimental data of SJLEDs for $25V \leq BV \leq 50$V [14]. Best results were obtained for $N \approx 2 \cdot 10^{17}$ cm$^{-3}$ and a minimum $d \approx 0.38 \mu$m, both defined by technology constraints. The SJLEDs ($L = 2 \mu$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 emission near this junction (this could not be observed in our 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.

We have performed extensive TCAD simulations to optimize the SJLED for $BV = 5$V and $15$V 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 unit cells of (a) the SJLED for $N = 2 \cdot 10^{17}$ cm$^{-3}$, $d = 0.38 \mu$m, $L = 350$nm (see also Fig. 2), (b) and (c) the optimized SJLED for $N = 10^{18}$cm$^{-3}$ and $d = 10$nm and $L=350$nm, respectively, $32$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).

![Image](image-url)
see Fig. 1(d). These lengths, 32nm resp. 350nm long, are then obtained from TCAD simulations of 15V (left) and 5V SJLEDs for \( N = 10^{16} \text{cm}^{-3} \) (top), 2\( \times 10^{17} \text{cm}^{-3} \) (middle) and 10\( \times 10^{16} \text{cm}^{-3} \) (bottom). In all cases \( d \) is varied for obtaining a constant field for \( d \approx 100 \text{nm} \) (\( N = 10^{16} \text{cm}^{-3}, 15V \)) and \( d = 10 \text{nm} \) (\( N = 2 \times 10^{17} \text{cm}^{-3} \) and \( 10^{18} \text{cm}^{-3} \)). One exception: for 5V and \( N = 10^{16} \text{cm}^{-3} \), \( d \cdot N \) has hardly any effect.

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

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.

![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.](image)

Finally, for \( BV \leq 5V \) 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

\[
\mathcal{E}_{\text{NLA}}(x,y) = \frac{5}{2} \cdot \frac{kT_e(x,y)}{q_\lambda_e},
\]

where \( T_e \) is the increase in electron temperature and \( \lambda_e \) is the mean free path of electrons (~65nm in Si). For both the p-i-n diode and SJLED holds [28]

\[
\Delta T_e = \frac{2q_\lambda_e}{5k} \left[ 1 - \exp \left( -\frac{x}{\lambda_e} \right) \right].
\]

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 \( \mathcal{E}_{\text{NLA},x}(x) < \mathcal{E}_x(x) \) \( (\mathcal{E}_{\text{NLA},y}(x) \) 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 \( (y \text{-direction}) \) field (~1.2 MV/cm) at nm-scale dimension, even a higher field than for the 5V 1D p\( ^{+} \)-n diode. Because \( \mathcal{E}_{\text{NLA},x,y} \) will then be higher than \( \mathcal{E}_{x,y} \), 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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