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Improved light extraction efficiency of complementary metal-oxide semiconductor hot carrier lights sources with the use of improved back-end-of-line light directing structures

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Abstract. Previous research has shown that the use of back-end-of-line (BEOL) light directing structures with silicon hot carrier light sources in a complementary metal-oxide semiconductor results in improved light extraction efficiency. This work focuses on the design of an improved back-end-of-line structure for improving light extraction efficiency when using substrate-based silicon light emitters. With the use of FRED optical engineering ray-tracing software, it was found that a significant amount of generated light is lost at the material interfaces of the optical structure, including losses due to significant internal reflections. Therefore, an optimized optical structure was designed to reduce internal reflections at the base of the structure. Simulation results show a 33.6% improvement in light extraction efficiency over the previously designed parabolic optical structure, over the visible spectrum. The light sources were tested using a parameter analyzer, radiometer, spectrometer, and goniometer. It was calculated that the luminance exiting the optimized optical structure had a 55.66-factor improvement over the control structure and a 1.35-factor improvement over the parabolic structure. Furthermore, the optimized structure had a 1.38-factor improvement in light extraction efficiency over the parabolic structure. Overall, the improved designed pipe-like BEOL light directing structure helped to improve the device luminescence and light emission direction from the light source, which invariably increased the light extraction efficiency.
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Keywords: complementary metal-oxide semiconductor; hot carrier electroluminescence; light; back-end-of-line; light extraction efficiency; light directing structures.

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1 Introduction

1.1 *Background*

Complementary metal-oxide semiconductor (CMOS) hot carrier light sources, based on reverse-biased silicon pn-junctions in avalanche, have been designed and integrated using a standard 0.35-μm CMOS process.[1–3] It has been found that the light extraction efficiency of CMOS hot carrier light sources is inefficient and can benefit from an improvement in light extraction.[4] It is possible to use back-end-of-line (BEOL) features, already present in a CMOS process, to form light directing structures that improve the extraction efficiency. This has been shown to improve both directionality and external optical power by a factor of 3.9.[4] However, directionality and external power efficiency are two separate performance attributes and we require accurate representation of each to better quantify the improvements gained by utilizing light directing structures on chip. Furthermore, approximately only 1% of the light emission from the light generated at the reverse biased junction exits the surface of the chip,[4] which emphasizes the inefficiency of current CMOS optical structures.

An analysis was undertaken to investigate the optical geometry and light extraction capabilities of hot carrier light sources in CMOS with BEOL light directing structures using a focused ion beam (FIB) and scanning electron microscope (SEM).[5] It was found that a significant amount of light radiation is lost due to total internal reflections (TIR) as a result of diffuse scattering, electromagnetic absorption, and reflection of light. These losses are caused by different media and their interfaces within the optical structure as well as the metal and via interconnects that make up the BEOL stack.[5] From the analyses, it was evident that for improved light extraction efficiency the TIR of the optical structures within needs to be reduced.

1.2 *Techniques for Improved Light Extraction Efficiency*

Two methods for improved light extraction efficiency were investigated. First, the design of an improved BEOL light directing structure and second the use of surface texturing, a method commonly used in the LED industry.[6–15] The design of CMOS hot carrier light sources allows for a single manufacturing process for both integrated circuitry and emissive light sources all on a single silicon substrate, without the need of postprocessing. This boosts both design configurability and robustness and gives the designer all the benefits that the platform provides. Surface texturing is a postprocess technique, which has proven to be invaluable in improved light extraction efficiency in the LED industry,[6–15] but will

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take away from the integrity and benefits of a single manufacturing process. Furthermore, the use of surface texturing only improves the light extraction of light radiation incident upon the exit surface of the light structure. Therefore, it was decided to investigate the design of improved light directing structures for improved light radiation propagation from the light-emitting junction toward the exit surface of the structure.

Once internal light radiation propagation is improved then a postprocess surface texturing technique can be implemented to further improve light extraction efficiency. One promising technique is the use of silicon dioxide nanosphere arrays, synthesized by the Stöber process, which are then spin cast and embedded into a polymer layer on top of the surface structure.[6]

2 Ray Trace Simulation of Improved Structures

From the FIB and SEM analysis of CMOS hot carrier light sources with parabolic BEOL light directing structures,[5] the size and dimensions of the optical structure and metal and via interconnects were recorded to allow for accurate simulation of the structure, and to allow for the design of an improved structure. Simulation software used was FRED Optical Engineering. The first ray trace design was the design of a control structure without any light directing structures for comparison of improvement in light radiation propagation and extraction efficiency.

2.1 *Parabolic BEOL Light Directing Structure*

The following design was that of the parabolic BEOL light directing structure. This was to simulate the light propagation from the junction through the BEOL stack and out the SiO_2/air exit surface interface. The design cross section of the parabolic BEOL optical structure is shown in Fig. 1, where it can be seen that the BEOL metal and via interconnects are placed in a parabolic-like structure, but represent a more step-like structure due to the fabrication procedure.

The premise of this design is to optimize the light radiation propagation reflection, of incident light, from the light-emitting junction off the BEOL light directing structure toward the exit surface of the CMOS structure. If the design was perfectly parabolic in nature this would be true, as incident light emitted from a specified focal point within a parabolic structure would result in optimized specular light reflection, but instead due to the nature of the fabrication process this is not true. From the FIB and SEM analysis, it was found that due to the nonuniform edge lapping of metal and via interconnects the layers were irregular at the edges and resulted in a structure with inconsistent internal diffuse reflectors.[5] Although improvements were made, the optimization and premise for this design were incorrect.[5]

The simulated ray trace of the parabolic BEOL light directing optical structure is shown in Fig. 2. From the ray-trace simulation, it is evident that the use of the light directing structure results in optimized light radiation propagation toward the surface of the structure with three distinct lobes, but what is also apparent is the magnitude of light radiation lost in the base of the structure as a result of TIR and the gap between where the BEOL stack starts and the light emission region. Therefore, it was hypothesized that optimization of electroluminescence propagation in the base of the structure will result in improved light extraction efficiency.

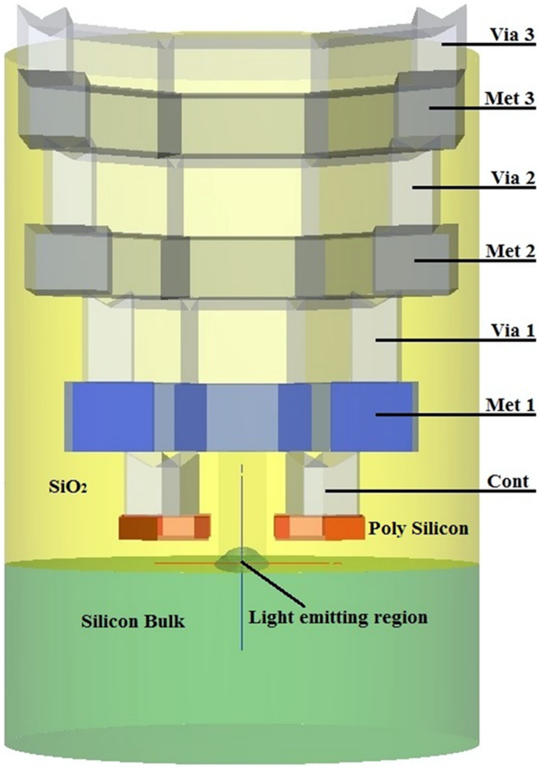

Fig. 1 Cross section of simulated parabolic BEOL optical structure.

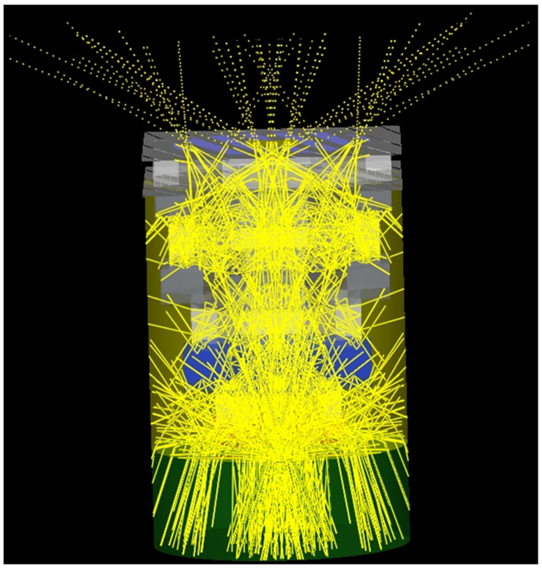

Fig. 2 Simulated ray trace of parabolic BEOL optical structure.

2.2 *Parabolic BEOL Light Directing Structure*

For the optimized BEOL light directing structure, it was decided to remove the polysilicon layer, as the contact layers will extend to the substrate allowing an improved area of initial light radiation propagation reflection at the base. Furthermore, a pipe-like structure was designed, with a constant inner diameter throughout the BEOL stack, to insure improved uniformity of the BEOL inner surface and to allow ample surface reflection of incident light radiation. The

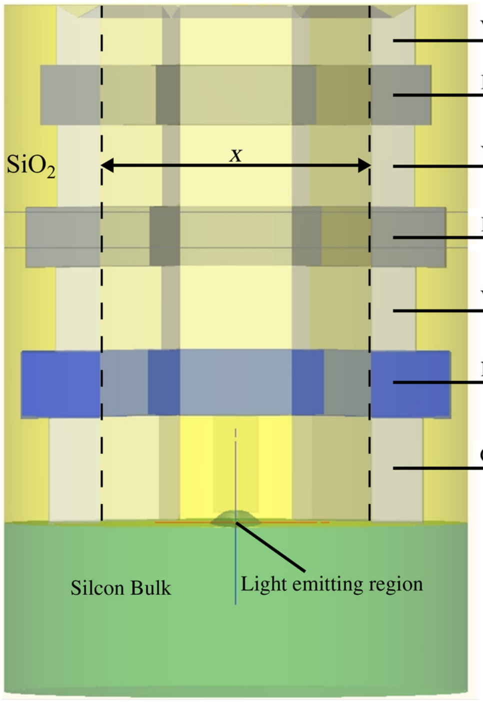

Fig. 3 Cross section of simulated optimized pipe-like BEOL optical structure.

design restrictions with CMOS are very stringent; therefore, there are many design limitations to adhere to. The design of the improved pipe-like BEOL optical structure is shown in Fig. 3. Furthermore, Fig. 4 shows the simulated ray trace of the pipe-like BEOL optical structure for comparison with Fig. 2.

The ray trace simulation was completed, and it was found that the light radiation reflection within the base of the structure improved. The ray trace simulations were taken across the spectrum of interest within this work, the visible spectrum, therefore wavelength (λ) from ∼400 to 700 nm. Table 1 shows the results of the ray trace simulations. The input power to the light-emitting junction was set to 1 W for easy calculation of integrated power incident upon the analysis surface at the exit surface of the simulated optical designs, to give a relative light extraction efficiency.

2.3 *Summary of Simulated Ray Trace Results*

From Table 1, it is evident that the pipe-like reflector results in improved light extraction efficiency across the visible spectrum. The optimized BEOL structure has an ∼33.9% improvement in light extraction efficiency over the previously designed parabolic optical structure. However, it is unmistakable how inefficient the optical structure of CMOS hot carrier light sources is, approximately only 2.73% of light generated at the junction exits the CMOS structure. Therefore, an additional simulation was undertaken to simulate the light extraction efficiency at the $\mathrm{Si/SiO_2}$ interface and was found to be ∼13.4%. Therefore, only 13.4% of electroluminescence at the light emission junction passes through the $\mathrm{Si/SiO_2}$ interface and then with the use of the optimized structure approximately only 22.39% of the remaining light radiation, propagates through the optimized BEOL stack and exits through the surface interface. This emphasizes just how inefficient the optical structure is within CMOS for hot carrier light sources.

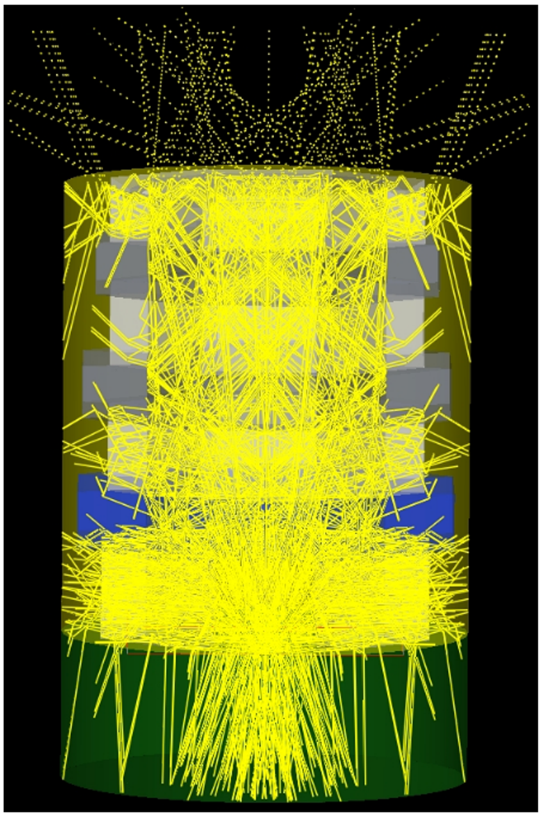

Fig. 4 Simulated ray trace of pipe-like BEOL optical structure.

Table 1 Light extraction efficiency table of results for simulated optical systems.

λ (μm)	Parabolic (%)	Pipe-like (%)	Control (%)	LEE improvement factor of pipe-like over parabolic structure
0.4	0.1999	0.2442	0.0840	1.221
0.45	0.7283	0.9398	0.3305	1.290
0.5	1.5525	2.0893	0.7296	1.346
0.55	2.2784	3.0935	1.0414	1.358
0.6	2.7627	3.7973	1.2669	1.374
0.65	3.1412	4.3459	1.4322	1.384
0.7	3.3012	4.6318	1.4860	1.403
Average	1.9949	2.7345	0.9101	1.339

3 Results

The control, parabolic, and optimized optical structures were designed and fabricated within a 0.35-μm CMOS process. The optical source and surface area for each optical source were identical for each BEOL optical structure. For measurement and calculation of results, a parameter analyzer was

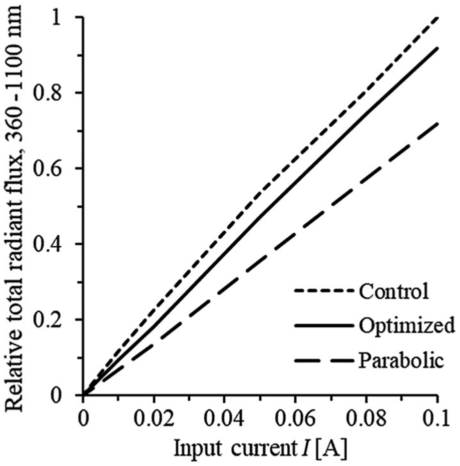

Fig. 5 Relative radiant flux as a function of input current.

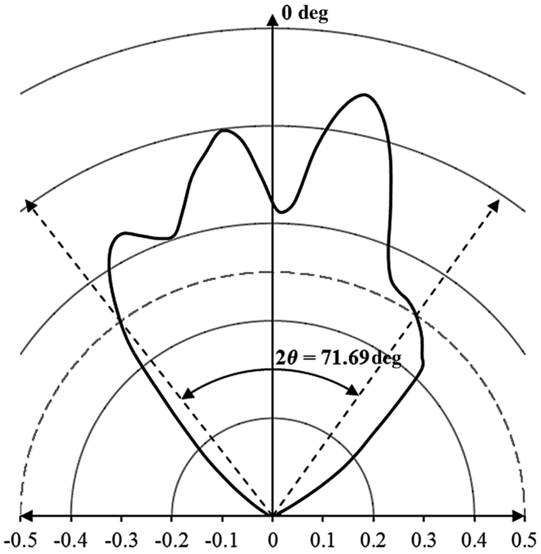

Fig. 7 2-D radiation pattern of the control optical light source.

used to record the IV characteristics of the devices. The relative magnitude of light radiation emission at the surface of the structure was measured with the use of a radiometer. Then, a spectrometer was used to obtain the respective spectrum of the optical sources, which was then coupled with the radiometer relative radiant flux to obtain the power spectral density for each optical source.

The radiant flux as a function of input current for the devices is shown in Fig. 5, where the relative radiant flux of both the control and optimized optical structures is improved in comparison to the parabolic optical structure. The reason the control total radiant flux is the largest is due to a large infrared radiant flux component. However, the visible spectrum is the spectrum of interest, and Fig. 6 shows the relative power spectral density of the optical light sources over the visible spectrum.

The next step was the use of a goniometer to determine the directionality and apex angle of the optical light sources, and this would allow calculation of luminance to accurately determine light extraction efficiency, as it combines both luminous flux and solid angle over a specified area all at the same input bias current for each optical source. The two-dimensional (2-D) radiation patterns for both the control and optimized optical structures are shown in Figs. 7 and 8, respectively.

From Figs. 7 and 8, the directionality for the optimized optical structure is improved when compared to the control optical structure. The apex angle for the parabolic structure was found to be slightly better than the optimized optical structure, but only ever so slightly at 11.65 deg. The results for the optical structures are shown in Table 2.

From Table 2, the use of BEOL light directing structures results in both improved directionality and light extraction efficiency when compared to a CMOS hot carrier light source without. With the use of luminance as the figure of merit for light extraction efficiency, the parabolic and optimized optical structures have a 41.13 and 55.66 factor improvement in luminance over the control structure, whereas the optimized structure has a 1.35-factor improvement in luminance over the parabolic structure. Furthermore, the total luminous flux of the optimized optical structure has

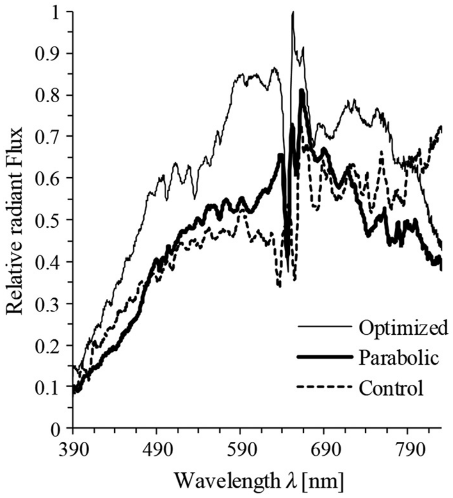

Fig. 6 Relative power spectral density of optical light sources over optical spectrum.

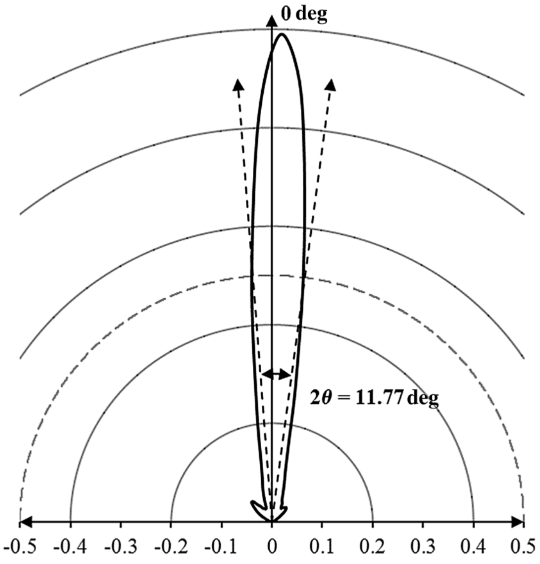

Fig. 8 2-D radiation pattern of optimized optical light source.

Table 2 Apex angle, solid angle, and luminance table of results over visible spectrum.

	Control	Parabolic	Optimized
Apex angle (deg)	71.69	11.65	11.77
Solid angle (sr)	1.1899	0.0324	0.0331
Luminance (cd/m^2)	77.58	3190.72	4318.16
Relative total luminous flux	1.00	1.12	1.55

a 1.55-factor improvement over the control and 1.38-factor improvement over the parabolic optical structure. Therefore, the optimized pipe-like BEOL optical structure results in improved light extraction efficiency and is an improved BEOL light directing structure.

4 Conclusion

The design of an optimized pipe-like BEOL light directing structure has resulted in a 1.35-factor improvement in luminance and a 1.38-factor improvement in light extraction efficiency over the previously designed parabolic BEOL light directing structure, and has resulted in an improved BEOL light directing structure for improved light extraction efficiency. Furthermore, the directionality of the light emission radiation pattern has also significantly improved.

The overall light extraction efficiency of CMOS hot carrier light sources is inefficient and requires further improvement. Furthermore, this work has shown that the design of improved internal BEOL light directing structures results in improved light extraction efficiency, but the magnitude is relatively minimal. For significant improvement in light extraction efficiency, the efficiency of light propagation from the light emitting region interface into the SiO_2 bulk needs to be improved.

Once internal TIR is reduced and light radiation propagation improved, surface texturing techniques can be used to further improve light extraction efficiency.

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